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Sound Sources and Level in the Oceans

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ABSTRACT

The standard definitions found in the American National Standards on Acoustics are applied to common sound sources used in both underwater acoustics research and in naval sonar systems operation. Recommend metrics are quantified for both continuous and transient sources of sound. The standard definitions are reviewed with theoretical sound source models. Requisite metrics are derived and applied to examples of energy sources of sound such as transients from a small omni explosive, an air-gun, a light bulb and a Dolphin. A generic model of surface ship sonar system emissions is developed as quantitative model. Active sonar transmissions are analyzed with the requisite quantitative metrics required to characterize these emissions. These results should be useful in environmental assessments, biological experiments and in the system design.

I. INTRODUCTION

Since the decision of the Navy to shift its operations as well as research and development to active sonar, attention has focused of the safe utilization of sound in the sea. In addition, the use of sound to probe changes in the oceanic thermal structure during long-term experiments such as the Acoustic Thermometry of Ocean Climate, ATOC, has further complicated the issue and posed the question of long-term safe or benign levels of exposure. The quantification of what constitutes an acceptable level of exposure is an important not only because of our increased use of high power and energetic sources but our awareness of the deleterious effects sound on marine mammals and the requirement of communication between different scientific disciplines.

The discussions and papers presented at the 126th Meeting of the Acoustical Society of America [1], Oceans 93 [2], and Oceans 94 [5] illustrated the confusion with respect to the application of national acoustical standards to the characterization of sound and source levels. This confusion has resulted in misleading reports such as the article by M. B. Browne in the October 19, 1993, the New York Times [4]. This article treated the decibel as an absolute unit and compared low frequency air-guns to ultrasonic transients from Dolphins, and the continuous rumble of large ships to the transient sounds from whales. In short the use of the decibel without specificity by members of the Acoustical Society reflected in his report enabled the blind comparison of a variety sounds in the ocean and inappropriate to decibel levels in air. This confusion regarding the specification of sound levels has also spread to "scholarly" works such as the National Research Council, NRC, monograph "Low-Frequency Sound and Marine Mammals"[5]; the purpose of which was "review the current state of knowledge and ongoing research on the effects of low frequency sound on marine mammals". Unfortunately this monograph may not have clarified this issue because mixed conventions, units, and measures (peak, root mean square, and square values) irrespective of frequency and bandwidth were used...

Of interest to here is the considerable debate concerning the use of levels and in particular the decibel. The use of the decibel in acoustics has an interesting yet torturous history. Several texts [6-11] have clearly written chapters on the use of units and the decibel. The text by Pierce is notable because of his historical sketch of the decibel; its introduction and use by Hartley [12] and Martin [13] as a transmission unit. One should note that the transmission unit ($10^{0.1}$) is the equivalent to the sensation unit; that is 1 unit corresponds to a multiplicative change of $10^{0.1}$ in power like quantities. This unit was the basis for the definition of the decibel. [11] Incidentally, the first introduction of the dB to the Journal of the Acoustical Society of America was by Knudsen [14, p. 58, n4]. The Pierce text clearly explains the correct use of the decibel in relation to measured acoustic quantities.

Editorial concerns about the use of System International, SI, units and the decibel in references [1-5] prompted the preparation of a peer-reviewed-editorial for the Journal of Oceanic Engineering to stimulate discussion and perhaps to initiate care in the use of levels and the decibel [11-13]. This editorial was also directly distributed to members of the oceanic and naval research communities concerned with the safety of the marine environment and the use of experimental sound sources in an attempt to clarify the quantification of levels based on the applicable ANSI standards, [18-23].

The second NRC monograph [24] "Marine Mammals and Low-Frequency Sound" attempted to update the review of [5] and focused on the knowledge of the response of marine mammals to low frequency sound. Again the discussion of the ATOC source level [24, p. 1, n.1] is confused and the characterization of the source compounded by the statement "acoustic pressure is expressed in watts per square meter" [24, p.13, n.2]. The problem with units is continued throughout the report and results in confusion concerning the applications of levels and the decibel. The specification of source level, in particular, has been an issue for some time although a clear applicable standard exists [16, 23].

In the 1950's, J.W. Horton of the Underwater Sound Laboratory responded to the confusion of his time with a proposal to eliminate the dB by using a logit. He stated "The term *decibel* has been used for quantities for which it is not the assigned designation. Confusion and error have resulted" [25, p.550]. Previously he had published an article with a preface written by the Standards Committee of the I.R.E [26]. These NRC reports are a reminder of the admonitions in this preface to Horton's paper by the I.R.E. Standards Committee [22] over their concern with the use of levels and the dB with out specificity:

"Which two values of power are meant when a standing-wave ratio is expressed in decibels? Which two values of power are meant when a television signal-noise ratio is expressed in decibels? Which two values of power are meant when the contrast range of a picture is expressed in decibels? Can you figure out what is meant when the statistical variance of a quantity, no matter what it is, is expressed in decibels? In short, have you noticed the meaning of decibel is being extended to a point of real ambiguity?

The Standards Committee of the Institute finds it so. The practice is so widespread that it is guardedly admitted in standard definitions, including some recently published by the IRE. Such official concession confuses rather than clarifies the issue."

These publications by Horton [6, 25, 26] provoked an unresolved debate on the subject of levels and decibels. However the current standard [23] clearly states a method, terminology and set of definitions which when correctly applied eliminate much of the ambiguity and as suggested by this editor when accompanied by the correct SI units should be very clear. Alas, if only they would be applied.

The most recent application or misapplication of the decibel concerns the analysis of the marine mammals stranding in the Bahamas during a naval exercise in the year 2000. This stranding was of societal concern and subsequently the Department of Commerce, D. Evans, and the Department of the Navy, G. England conducted an exhaustive and expensive evaluation of this incidence; however even though these departments have access to talented scientists, they did not use the current standards rather they incorrectly redefined the decibel and sonar equation terms [27].

***"Decibel (dB):** Decibel is a dimensionless ratio term that can be applied to any two values; temperature, rainfall, the number of jellybeans in a jar, or sound. Decibels are expressed as 10 times the logarithm of the ratio of a value (V) to its reference value (Vref), or: N decibels (dB) = 10*log (V/Vref) The decibel originated in electrical engineering measurements of transmission line losses, but it is also physiologically significant in that the response of biological ears to sound is logarithmic. Decibels should always be accompanied by a reference value that defines the ratio being expressed, unless the reference is clearly stated at the start of the paper."*

The above definition confuses the relative levels and the decibel, the latter being the logarithm to the $10^{0.1}$ of a power ratio where a relative level is simply the order of magnitude. This was Horton's point. The report continues with additional definitions at variance with the standards [23] that are basically incorrect.

"In this paper all references to dB that are not accompanied by a specific reference value are dB of sound pressure level (SPL), referenced to 1 micro Pascal of pressure. Other commonly used acoustic measures, such as Sound Energy Level (SEL), also commonly expressed in dB ratio terms, will be specifically stated as being something other than sound pressure, and a different reference term, such as 1 second-second squared, will indicate that a value other than SPL is being discussed. A further distinction that needs to be kept in mind is whether the dB value is a Received Level (RL) or Source Level (SL). For acoustic sources, the convention is to express the power of the source in Sound Pressure Level at a distance of 1 meter from the acoustic center of the source. In many cases, especially for large sources, this is a theoretical number that never actually exists in the physical world, but is calculated from received levels measured at distances greater than one meter from the source. The source level of a sonar may be 235 or more, but the sound pressure at any one point away from the source is affected by the spreading

of sound in all directions, and by absorption, reflections, scattering and other phenomena (discussed in more detail in the section on Acoustic Modeling). The physics of the propagating medium will determine whether the received level at a given point is 170, 180 dB, or some other value for a stated source level. While the source levels of the Navy sonars described here were generally 235 dB (sound pressure level), the received sound pressure level at any point more than a meter from the source would have been lower."

This report is indeed regrettable because it does not clearly state the impact of naval sonar systems on the marine environment with well defined terminology or conventions found in the current standards [18-23]. This is a matter of national concern especially when the two agencies of the federal government responsible the national standards for underwater acoustic err. When calculations are performed without a clear understanding of dimensionality of the quantities being estimated, then questions arise concerning their correctness and misunderstanding and confusion results. Most important it prevents careful comparisons with laboratory studies of deleterious effects on marine species. Recently the debate has focused on the Low Frequency Active Sonar and the sound emitted at the lower frequencies. Whether this system will have either a null or deleterious effect on the oceanic and environment and marine mammals will not be resolved unless the quantification of the sound source and resulting sound fields are correctly specified. The purpose of this paper is not to develop new metrics or standards but simply to illustrate the application of the current standard to this important problem.

This paper does not recommend parameters to be used by biological studies to guide the characterization of damage mechanisms; rather it presents the correct metrics, SI units and Level conventions, concerning the continuous, transient and impulsive sounds which can be used to characterize the parameters used in biological studies.

II. Standard Definitions

Levels are by definition relative units. In acoustics the term level refers to the logarithm of a non-dimensional ratio (R). The logarithm to the base ten (Log_{10}) or the natural logarithm (Ln) may be used however this paper concerns the use of Log_{10} and the deci-Bel.

$$Level \equiv Log(R) . \tag{1}$$

In general the ratio R can be determined for any quantity; however the Bel is defined as a unit of level when the logarithmic base is 10 and R is the ratio of two powers (PR).

$$Bel \equiv Log_{10}(PR). \tag{2}$$

The important point is that we have the ratio of powers or a ratio proportional to the ratio of powers. The deci-Bel (dB) is defined as one tenth of a Bel and again requires a ratio of powers.

$$dB \equiv Log_{10^{1/10}}(PR) = 10 \cdot Log_{10}(PR). \tag{3}$$

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This definition represents the basic problem acousticians have with the use of the decibel, a level based on a power ratio. Simply put, pressure is usually measured and intensity [W/m²] is estimated based on the plane wave equation, $I = p_p^2 / 2\rho c$. When a power ratio is formed, $PR = I / I_{ref} = p^2 / p_{ref}^2$, the factor ρc cancels. Valid comparisons can be made between pressure levels in the same fluid with small variations in ρc. However when the pressure levels in two media are compared such as air and water; one must account for the ρc difference. The power ratio for equal pressure amplitudes in air and water is

$$PR = I_{air} / I_{water} = \rho_w c_w / \rho_{air} c_{air} \approx 4.4 10^3 \rightarrow \approx 36\,dB.$$

Given the power ratio, $PR = \Pi[W] / \Pi_{ref} = I / I_{ref} = p^2 / p_{ref}^2$, several reference quantities can be used. The convention used in underwater acoustics is to choose the $p_{ref} = 1\mu Pa$, this corresponds to an $I_{ref} = 0.67 \cdot 10^{-18}\, W / m^2 = 0.67\, aW / m^2$. Because one may choose any of the above references the following simple conventions can be used.

$$L_{xxx}\, dB\, re\, xxx\quad or\quad xxx\, Level\, dB\, re\, xxx. \tag{4}$$

The modifier xxx should be that of the reference quantity such as power, intensity or pressure. When the reference is pressure then one has Pressure Level dB re 1 μPa and when the reference is intensity one would have Intensity Level dB re 1 W/m².

II.1 Harmonic Sound

The fundamental quantity observed or measured in acoustics is the real acoustic pressure. In the case of a simple harmonic *monopole* source, *i.e. a spherical source when the size of the source becomes vanishing small,* the radiated pressure, p[μPa] where 1 μPa $=10^{-6}$ N/m², to the far field is an outgoing spherical wave

$$p(r,t) = -(ik\rho cS / 4\pi)\exp(ik(r-ct)) / r = -iQ_s \exp(ik(r-ct)) / r \tag{5}$$

Q_s [μPa·m] is the monopole amplitude and $\rho \omega S / 4\pi$ [μ (kg/m³)(rad/sec)(m³/sec)] the source-strength amplitude. The real pressure is

$$p(r,t) = (Q_s / r)\sin(k(r-ct)) = (Q_s / r)\sin(\omega(r / c - t)). \tag{6}$$

The particle velocity, u(r, t) [m/s] is given by

$$u(r,t) = (Q_s / \rho cr)\sin(\omega(r / c - t)) \tag{7}$$

The source strength Q_s is related to the intensity since the instantaneous intensity, I(r, t) [W/m²], is the product of the pressure and particle velocity.

$$I(r,t)=u(r,t)p(r,t)=(Q_s^2 / \rho c r^2)\sin^2(\omega(r/c-t))$$
$$=(Q_s^2 / 2\rho c r^2)(1-\cos(2\omega(r/c-t))). \tag{8}$$

The time averaged intensity, I(r), at a given radial distance is

$$I(r)=<I(r,t)>_T=(1/T)\cdot \int_0^T I(r,t)dt = (Q_s^2 / 2\rho c r^2), \text{[W/m}^2]. \tag{9}$$

When we choose a reference distance of 1m we obtain

$$I(r = 1m) = (Q_s^2 / 2\rho c), \ [W/m^2]. \tag{10}$$

This time average intensity is the average rate of energy flow through a unit area normal to the direction of propagation, (W/m^2=J/m^2·sec=N·m / m^2·sec). Letting $p_p=Q_s$ and $u_p=Q_s/\rho cr$ then we have

$$I(r)=<I(r,t)>_T = p_p u_p / 2 = p_p^2 / 2\rho c = p_{rms}^2 / \rho c = \rho c u_p^2 / 2 = \rho c u_{rms}^2. \tag{11}$$

The inclusion of the particle velocity terms in Eq.11 is relevant to measurement of ambient noise with velocity and pressure-gradient sensors.

The source level, SL, of a harmonic source is thus defined as the ratio of total radiated power by the source to a reference power at a distance of 1 m. For an omni-directional source one has

$$SL_o = 10 \ Log[\ I(1m)/I_{ref}\ ] = 10 \ Log(\ (p_o/1 \mu Pa)^2\ ]), \ [dB \ re \ 1 \mu Pa \ @ \ 1m]. \tag{12}$$

If the source is directional, the intensity is measured on the main response axis, I_o(1 m) along with the relative directional pattern d(θ,φ).

$$W_s = \iint I_o d(\theta,\varphi)\sin(\theta)^2 d\theta d\phi = I_o \cdot 4\pi \cdot di$$
$$PR = I_o \cdot 4\pi \cdot di / I_{ref} \cdot 4\pi = I_o \ di / I_{ref} = (p_o / p_{ref})^2 di \tag{13}$$
$$SL_d = 10Log[(p_o / p_{ref})^2 di] = SL_o + DI$$

This calculation of intensity is for a continuous harmonic source. In common practice, measurements performed with linear filters or Fourier Transforms; the quantity p(r, ω) is observed and the intensity

$$I(\omega_0,r)=1/2 \operatorname{Re}(p(r,\omega_0)\cdot p(r,\omega_0)^* / \rho c), \ [W/m^2]. \tag{14}$$

This quantity is related to the mean square pressure by Parseval's Theorem since for a harmonic source only a single frequency line occurs. For this reason the intensity for a

harmonic source is not bandwidth corrected. The reference intensity is usually taken as that corresponding to a either peak or root mean square pressure amplitude of 1 μPa.

$$I(\omega_0, r)/I_{ref} = [(1/2)p^2]/[(1/2)p_{ref}^2] = p_{rms}^2 / p_{ref-rms}^2. \qquad (15)$$

II.2 Transient Sound

An important category is the transient or impulsive sounds. The acoustic energy flux density of a transient or an impulse signal can be determined at one meter distance:

$$E[J/m^2] = (1/\rho c) \int_o^{t_o+T} p(1,t)^2 dt = E_x / \rho c$$

$$[(\mu Pa)^2(s)/(kg/m^3) \cdot (m/s)] \qquad (16)$$

where E_x is the sound exposure. To form a ratio that is proportional to a power ratio requires a reference energy flux density which is chosen to be a 1 second gated sine wave with amplitude of 1 μPa:

$$E_{ref} = E_{xref} / \rho c = p_{ref}^2 \cdot t_{ref} / \rho c = [1\mu Pa^2 \cdot s]/\rho c ; \quad r = 1m. \qquad (17)$$

The reference could also be chosen to be a gated sine wave with a reference energy flux $E_{ref} = 1$ J/m^2 or a total energy flux of $E_{Tref} = 1$ J. This would be the preferred method because it lacks ambiguity. However it is not common practice since the ρc factors for the reference and the measured cancel. It is important when comparing levels in two different fluids.

II.2.1: Energy Flux Source Level

The energy flux density ratio is proportional to a power ratio; thus:

$$E/E_{ref} = E_x / E_{xref} = (\int_o^{t_o+T} p(1,t)^2 dt)/ p_{ref}^2 t_{ref}; \quad r = 1m. \qquad (18)$$

This ratio of the energy flux density source strengths can be converted to an Energy Flux Density Source Level by

$$EFDSL = 10 Log_{10}[E/E_{ref}], \, dB \, re \, ((1\mu Pa^2) \cdot (1s)) @ 1meter. \qquad (19)$$

If the reference is taken as $E_{ref} = 1 J/m^2$ then

$$EFDSL = 10 Log_{10}[E/E_{ref}], \, dB \, re \, (1J/m^2) @ 1meter. \qquad (20)$$

At any range r, a ratio of either energy or exposures [19] can be formed to obtain the sound exposure ratio and Sound Exposure Level, SEL or L_E:

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$$SEL = 10 \cdot Log_{10}(E_x / E_{xref}) = 10 \cdot Log_{10}(E_x / p_{ref}^2 t_{ref}) , \quad [dB\,re\,((1\mu Pa^2)(1s))].. \qquad (21)$$

With $E_{ref} = 1\,J/m^2$:

$$SEL = 10 \cdot Log_{10}(E_x / E_{xref}), \quad [dB\,re\,(1\,J/m^2)]. \qquad (22)$$

II.2.2: Spectral Density of a Transient

The spectral density of a transient may be obtained by using Fourier Transform relationships with the following conventions:

$$p(t) = \int_{-\infty}^{\infty} P(\omega)\exp(-i\omega t)d\omega \quad with \quad P(\omega) = (1/2\pi)\int_{-\infty}^{\infty} p(t)\exp(i\omega t)dt,$$
$$p(t) = \int_{-\infty}^{\infty}\{(1/2\pi)\cdot\int_{-\infty}^{\infty} p(t')\exp(i\omega t')dt'\}\exp(-i\omega t)d\omega. \qquad (23)$$

The continuous version of Parseval's Theorem (Rayleigh's Energy Theorem or Plancherel's Theorem) is

$$\int_{-\infty}^{+\infty}|p(t)|^2 dt = 2\pi \cdot \int_{-\infty}^{+\infty} P(\omega)\cdot P(\omega)^* d\omega = \int_{-\infty}^{+\infty} P(f)\cdot P(f)^* df = \rho c E = E_x . \qquad (24)$$

The quantity $E_{sd}(f) = |P(f)|^2 / \rho c$ is the energy spectral density [J/(m^2- Hz)] and is the preferable designation with a reference quantity of [1 J/m^2-Hz]; or simply as before $|P(f)|^2, [(\mu p)^2 \cdot s/Hz]$. This quantity can be used when normalized by a reference energy spectral density $E_{ref,sd} = (1\mu Pa)^2 \cdot s/Hz$ to yield the Energy Spectral Density (ESD) Level:

$$Energy\,Spectral\,Density\,Level = 10 \cdot Log\,(E(1\,Hz\,band)/((1\mu Pa)^2 \cdot s/Hz))$$
$$= ESDL\,[dB\,re\,((1\mu Pa)^2 \cdot s/Hz)] \qquad (25)$$

II.2.3: The Impulse

A useful description of a transient is the Impulse, I_{imp}. The impulse is defined as

$$I_{imp} = \int_0^{T_o} p(1,t)dt \quad ; \quad [\mu Pa\,s]. \qquad (26)$$

The constant T_0 is the time of the first sign reversal after the occurrence of the peak pressure. The pressure p(1, t) is the pressure measured in the far field and extrapolated to 1 m. This metric may not have sonar significance but may have a role in the assessment of transient acoustic pressures on marine life. The logarithmic form is seldom used. [17]

II.3 Steady Sound

Sound which is a continuous bounded, non-periodic and stationary poses a problem for Fourier analysis. The Fourier integrals are infinite integrals and consequently convergence must be considered. Eq. 24, Parseval's Theorem states the problem. If the integral of $|p(t)|^2$ converges then the integral of $|P(f)|^2$ converges. If the pressure variation is random but stationary the $|p(t)|^2$ does not diminish as $t \to \infty$ and the integral will not converge. However if we restrict the form of p(t) such that

$$p(t) = 0, \quad -\infty < t < -T/2 \; ; T/2 < t < +\infty$$
$$p(t) \neq 0, \quad -T/2 < t < +T/2 \tag{27}$$

then for large but finite T

$$\int_{-\infty}^{+\infty} |p(t)|^2 \, dt \to \int_{-T/2}^{+T/2} |p(t)|^2 \, dt = T < p(t)^2 >_T = 2\pi \int_{-\infty}^{+\infty} |P(\omega)|^2 \, d\omega = \int_{-\infty}^{+\infty} |P(f)|^2 \, df \tag{28}$$

where
$$P(f) = \int_{-T/2}^{+T/2} p(t) \exp(i2\pi f \, t) dt .$$

These integrals decrease at a sufficient rate as $\omega = 2\pi f \to \infty$ to ensure convergence for large but not infinite values of T.

$$< p(t)^2 >_T = [2\pi/T] \int_{-\infty}^{+\infty} |P(\omega)|^2 \, / d\omega = [1/T] \int_{-\infty}^{+\infty} |P(f)|^2 \, df$$

$$< p(t)^2 >_T \, / 2\pi = \int_{-\infty}^{+\infty} (|P(\omega)|^2 /T) d\omega \text{ and } < p(t)^2 >_T = \int_{-\infty}^{+\infty} (|P(f)|^2 /T) df \tag{29}$$

$$(|P(\omega)|^2 /T) \text{ and } (|P(f)|^2 /T) \text{ are spectral densities per unit time.}$$

For this case on bounded, non-periodic, and stationary pressure fluctuations we can define time varying means and mean square quantities for large T.

$$< p(t) >_T = (1/T) \int_{-T/2}^{+T/2} p(t) dt \text{ and } < p(t)^2 >_T = \int_{-\infty}^{+\infty} |P(f)|^2 \, df \tag{30}$$

II.3.1: The Auto-Correlation Function

The question naturally asked is what happens as a function of time? The Auto-Correlation function is useful for this purpose.

$$\Gamma_p(\tau) \equiv \lim_{T \to \infty} \left[(1/T) \int_{-T/2}^{+T/2} p(t) p(t+\tau) dt \right]$$

$$\to \Gamma_p(0) \equiv \lim_{T \to \infty} \left[(1/T) \int_{-T/2}^{+T/2} p(t)^2 \, dt \right] = < p(t)^2 >_T \tag{31}$$

Since the Fourier Transform is a more complete description we have

$$F\{\Gamma_p(\tau)\} = (1/2\pi)\int_{-\infty}^{+\infty}\Gamma_p(\tau)\exp(-i\omega\tau)d\tau \to 2\pi P(\omega)P(\omega)^* / T \qquad (32)$$

Thus the Fourier Transform of the Auto-Correlation function is $(2\pi/T)$ times the spectral density $|P(\omega)|^2$ of p(t).

II.3.2 The Power Spectral Density

Continuing with the stationary but random pressure fluctuation we need to consider sampling. Each time series of p(t) which is observed is one member, a sample member of the family of all possibilities, the ensemble. Let the ensemble be represented by {p(t)} and $p^j(t)$ be the jth sample of the Random Process {p(t)}. If the variations of the mean, mean square and autocorrelation of p(t) exhibits: significant variation with time the process is self non-stationary; no significant variations with time the process is weakly self stationary; and if all moments of p(t) show no variation with time the process is strongly self stationary. If the moments are same for each jth sample of T seconds duration and independent of t then the process is ergodic.

For $p^j(t)$ which vanishes everywhere outside the interval $t_1 - T/2 < t < t_1 + T/2$ and there is no dependence on t_1 the average power or average energy over the interval is

$$P_p^j(T) \equiv E_p^j(T)/T = (1/T)\int_{t_1 - T/2}^{t_1 + T/2} p^j(t)^2 dt \qquad (33)$$

By Parseval's Theorem

$$P_p^j(T) \equiv E_p^j(T)/T = \int_{-\infty}^{+\infty}\{|P^j(f)|^2 /T\}df . \qquad (34)$$

$$W_p^j(f)_T \equiv 2|P^j(f)_T|^2 /T \to P_p^j(T) = \int_0^\infty W_p^j(f)_T df \qquad (35)$$

Since $W_p^j(f)_T$ is an even function of f , we do not need the negative frequencies and the factor of 2 in the definition above accounts for the change in limits. We can then define a linear average as

$$<P_p(T)>_{NT} = 1/N\sum_{j=1}^{N} P_p^j(T) = 1/N\sum_{j=1}^{N}\int_0^\infty W_p^j(f)_T df \qquad (36)$$

If the process is ergodic one can perform an ensemble average to obtain

$$<P_p(T)>_e = <P_p^j(T)>_e = \int_0^\infty <W_p^j(f)_T>_e df = W_p(f)_T \qquad (37)$$

For ergodic wide sense stationary processes one has

$$< P_p(T) >_{NT} = < P_p(T) >_e = W_p (f)_T \qquad (38)$$

The expected value of the power spectral density is also related to the covariance function, K , as follows as a direct consequence of the Wiener-Khintchine Theorem

$$W_p (f)_T = 2 F\{K_p\} = 2 \int_{-\infty}^{+\infty} K_p \exp(i\omega t) dt = < (2/T)|F(p(T)|^2 >_e \qquad (39)$$

Eq.32 states that the Fourier transform of the autocorrelation function is equal to 2/T times the spectral densities. Thus we have

$$W_p (f)_T = < (2/T)|F(p(T)|^2 >_e = < F\{\Gamma(\tau)\} >_e$$
$$\rightarrow < \Gamma_p(\tau) >_e = (1/2) \int_{-\infty}^{+\infty} W_p (f)_T \exp(-i\omega\tau) df = K_p(\tau) \qquad (40)$$

The final measure of the of the stationary statistical noise is the power spectral density

$$W_p (f)_T = < F\{\Gamma(\tau)\} >_e = < F\{K_p(\tau)\} >_e$$
$$= 2\pi < P(\omega)P(\omega)^* > /T = < P(f)P(f)^* > /T \qquad (41)$$

Thus the power spectral density level is referenced to a W/m^2-Hz or 1(μPa)^2/m^2-Hz as the natural units of the measurement.

$$\text{Power Spectral Density Level} \equiv 10 \cdot Log_{10}[W_p (f)_T / W_{p,\text{ref}} (f)_T]$$
$$= 10 \cdot Log_{10}[(< p^2(t) >_{NT} / \Delta f)/((\mu Pa)^2 / Hz)] \; ; [dB \, re \, (\mu Pa)^2 / Hz)]. \qquad (42)$$

III. Ocean Acoustics Sound Sources

This section applies the standard definitions discussed previously to several examples of oceanic noise sources. Theses noise sources are either part of the natural background or are used in oceanic sound transmission measurements.

IV.1: The Surface Ship

Shown in Fig. 1, [31], is one of the rare measurement examples of surface ship radiated noise obtained in the deep ocean (Northern Pacific: 137° 00' W, 27° 35' N). The measurement hydrophone was at a depth of 4,850 m, some 740 m below the critical depth- that is the depth at which the near surface maximum in the speed of sound equals the speed of sound at that depth. Thus only noise sources within a direct path of the hydrophone are important. The measured Pressure Spectrum Level [dB re {(μPa)^2/Hz}] shown in Fig.1 has common characteristics of the radiated sound from a surface ship [32, 33]. The ordinate is that of the author [31] and is labeled as dB re $\mu Pa / \sqrt{Hz}$. This label

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is a remnant from the early sixties and is equivalent to dB re $(\mu Pa)^2 / Hz$. This practice was one of the reasons that spectrum levels often have ambiguous ordinate labels [32].

The lower spectrum shows the ambient noise floor composed of leakage from the sound channel, noise from above, and seismic noise coupled through the water sediment interface. One can readily see that the natural noise level in absence of whales and other biologics is less than $55\,dB\,re\,(\mu Pa)^2 / Hz$ for $f < 50 Hz$ and $45\,dB\,re\,(\mu Pa)^2 / Hz$ for $100 < f < 500\,Hz$. The radiated noise spectrum from the freighter is at a much larger level and can be taken as representative of the true radiated spectrum. This spectrum consists of blade and shaft rate lines superimposed on a broad spectrum with levels increasing at approximately 6 dB per octave from 10 Hz to 50 Hz, a broad maximum between 50 and 100 Hz, a decrease of 12 dB per octave from 100 to 300 Hz, and a decrease of 6db per octave above 300 Hz. The prominent line at $\sim 27 Hz$ has a pressure spectrum level of 107 db re $[(\mu Pa)^2/Hz]$. Assuming the following "dipole like" signal model , the source level can be estimated:

$$I(r_{om}, r_{om}, f) = I_o(f) \cdot \sin^2(\theta_{om}) / r_{om}^2$$
$$\rightarrow RL(r_{om}, \theta_{om}) = 10\,Log[I(r_{om}, r_{om}, f)/I_{ref}] \tag{43}$$

$$RL(r_{om}, \theta_{om}) = 10\,Log[I_o(f)/I_{ref}] + 10\,Log[\sin^2(\theta_{om})] - 20\,Log[r_{om}]$$
$$SL_o(f) = 10\,Log[I_o(f)/I_{ref}] = RL(r_{om}, \theta_{om}) - 10\,Log[\sin^2(\theta_{om})] + 20\,Log[r_{om}] \tag{44}$$

$$\Pr essure\,Source\,Level: SL_o(f) = RL(r_{om}, \theta_{om}) + 80.3\,dB \quad \{dB\,re[(\mu Pa)^2]@\,1m\}. \tag{45}$$

The variables r_{om} and θ_{om} are the actual values of the slant range and angle to the surface ship at its closest point of approach. Under these conditions equivalent omni level is

$$\Pr essure\,Source\,Level: SL_o(27\,Hz) = 177.3\,dB\,re\,(\mu Pa)^2\,@\,1m; \tag{46}$$

and the total power radiated is

$$P_{rad} = I_o(27\,Hz) \cdot 2\pi \cdot \int_0^{\pi/2} \sin^2(\theta)\cos(\theta)d\theta$$
$$= I_o(27\,Hz) \cdot 2\pi/3 \tag{47}$$

$$Intensity\,Source\,Level\,ISL_{onb} = 10\log(P_{rad}/P_{ref}) = 181\,dB\,re[(\mu Pa)^2 \cdot m^2]$$
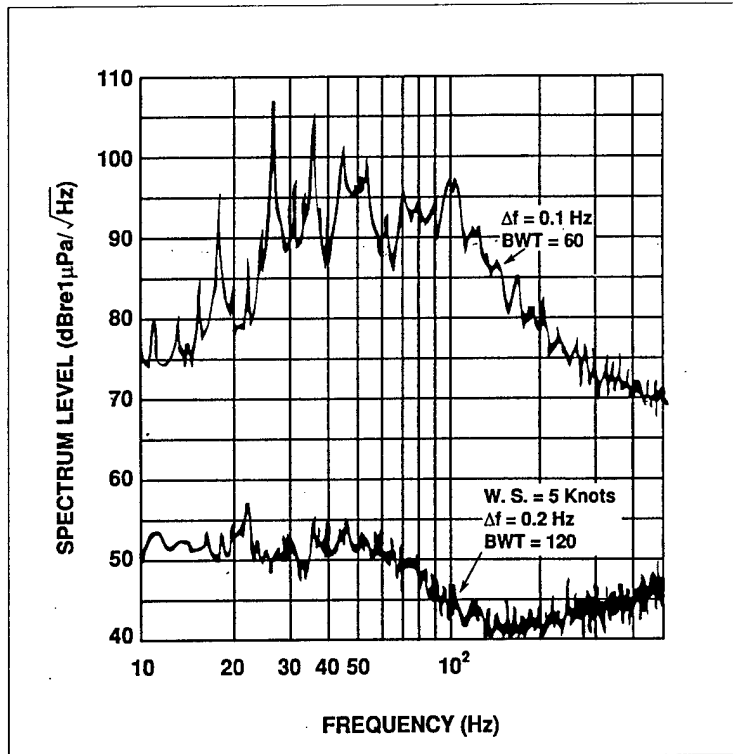$$Power\,Source\,Level\,P_{rad}\,SL_{onb} = -0.76\,dB\,re\,(1\,W), [0.84\,W\} \tag{48}$$

Figure 1, This measurement of the radiated noise from s 12,000 ton freighter passing at a horizontal distance of 7 km ($r_{om} = 8,516\,m\,and\,\theta_{om} = 55^{\circ}$)and with a hydrophone at a depth of 4, 850m was obtained by Wittenborn in 1976 [31].

The broad band spectrum can be integrated, eliminating the lines, to obtain the total broad band power, P_{rad}, from 0 to 600 Hz. Again we assume the above simplified source model as follows:

$$P_{rad} = \int_0^{f_u} df \int_0^{2\pi} d\phi \int_0^{\pi/2} I_o(r,f)r^2 \cos(\theta)d\theta. \tag{49}$$

The spectrum can be divide into frequency intervals with the appropriate transmission factor used previously to yield the source levels and the total radiated power as follows:

$$\Pr essure\,SourceLevel : SL_{obb} = 197\,dB\,re[(\mu Pa)^2]\,@\,1m$$
$$Intensity\,Source\,Level : SL_{obb} = 15\,dB\,re[W\,/\,m^2] \tag{50}$$
$$Power\,Radiated\,Source\,Level : P_{rad}SL_{obb} = 18\,dB[1W\} : [\approx 70W]$$

The interesting fact concerning surface ship radiated noise is the actual acoustic power radiated, on the order of 70 W. Even if these levels have increased by a factor of 4, current radiated noise levels would be less than 300 W.

IV.2: Explosives, Air Guns, Light Bulbs and Dolphin Clicks.

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A variety of impulsive sources are employed by man and animals in underwater sound. Explosives and air guns are employed in the seismic industry to perform sub-bottom profiling for oil exploration. Naval investigators use explosives and air guns for sound transmission and echo location studies. In these applications coherent arrays of these sources can be used to increase source directivity and the energy flux source levels. Light bulbs are a repeatable source that produces a short transient useful in the location of array elements and other objects. Usually these light bulbs are lowered to depth by a cable and a striking device initiates the collapse process. Because of the similarity of the transient waveform a dolphin click is also included. I have not included a 20 Hz/ 20 cycle Whale sound but it also falls in this category.

These transient sounds are of interest because it is common practice to use either peak or peak-to-peak pressures in the determination of source levels. Since a level is defined as the logarithm of any ratio; the peak pressure level is defined here as;

$$PPL = Log[((p_p / \mu Pa)^2)^{10}] = 20 Log[p_p / \mu Pa], \quad level\ re\ \mu Pa.$$

This use of peak pressure source level, dB re μPa, is not is no advisable since peak pressure ratios are not in general proportional to power ratios. The source level is defined in the standards as the measurement of the mean square pressure on the main response axis of the radiator. This measure when divided by a reference mean square pressure yields a level that when corrected for spreading loss becomes a source level referenced to 1 meter distance. The rational behind this definition is that the ratio of mean square pressures is proportional to a ratio of powers and consequently a ratio of energies. The use of peak pressure neglects the frequency or time spread of the waveform and is thus a poor measure of source level and is at variance with the definition of a deci-Bel.

As mentioned Section II, the characterization of a transient can best be accomplished using the energy of the transient, the transient averaged intensity and the impulse. Below are the expressions for three classic transient waveforms:

1.) Gated Continuous Wave of duration T_p with repetition T_R:

$$Energy \quad E = P_o^2 T_p / 2\rho c \ ;$$

$$Transient\ Avgerage. \quad <I>_{T_p} = [P_o^2 / 2\rho c] \cdot [T_p / T_R \}; \quad (51)$$

$$Im\ pulse\ I_{imp} = P_o T_o / \pi$$

2.) Exponential Wave with characteristic decay time T_e and repetition T_R:

$$Energy: \quad E = P_o^2 T_e / 2\rho c;$$

$$Transient\ Average: \quad <I>_{T_e} = [P_o^2 / 2\rho c] \cdot [T_e / T_R]; \quad (52)$$

$$Im\ pulse: \quad I_{imp} = P_o T_e$$

3.) Dampened Sinusoid with period T, decay time T_e and repetition T_R:

$$Energy: P_o^2 T_e / 4\rho c;$$

$$Transient\ Average:\ <I>_{T_e} = [P_o^2 / 4\rho c] \cdot [T_e / T_R];\qquad(53)$$

$$Im\,pulse: I_{imp} \approx P_o T / 2\pi$$

Since most of the examples that follow approximate one of these generic types, one can immediately see that the product of a peak pressure, P_o, and a characteristic time, T_e, is required. This fact is the prime reason levels based on peak pressure alone have little comparative utility.

Fig. 2 shows the classic conceptual sequence of an explosion in water. The properties of the explosive can affect the initial shock wave, the rate of reduction of peak pressure with range, and the increase of the time constant of the exponential tail with range. Both are nonlinear and detailed studies have been performed on this subject. However since the product of $P_o^2 T_e \rightarrow 1/r^2$ one can use an energy flux source level to describe this process.
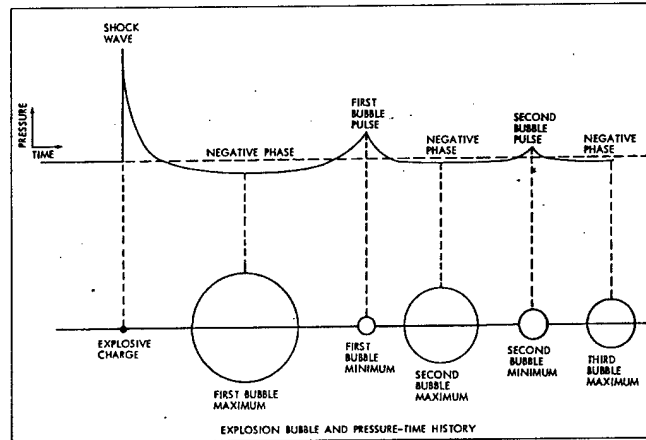

Fig. 2 A schematic of an underwater explosion illustrating the shock wave and rebound and collapse pressure pulses

Figure 3 shows a typical small omni explosive, composition B plastic, at a range of 24 meters. The shock waves are repeated at the bubble repetition frequency and are readily observed. Also shown is the Energy Flux Spectral Density- ESD- versus frequency with spectral nulls corresponding to the repetition frequency.
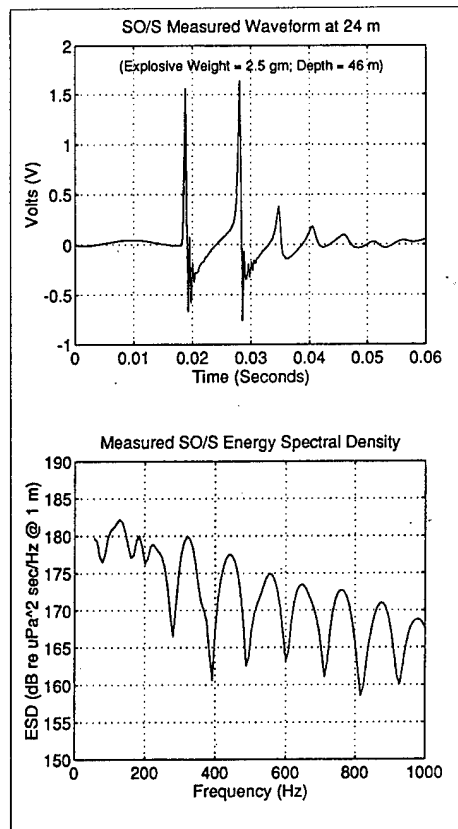
Fig. 3: The voltage (pressure) time history and energy spectral density versus frequency for a small omni-directional explosive at a distance of 24 and a source depth of 46 meters in water 100m deep. (Hydrophone sensitivity is -230 dB re (1 v/μPa)); Energy Flux Spectral Source Level is ESDL = 203 dB re ((μPa)^2-s) @ 1m in the 50-800Hz Band).

If all wave forms were this clear our problem would be straightforward; however most waveguides are doubly spread, frequency and time. This effect can be observed in Fig. 4 where the same explosion is observed at a distance of 10 km. The signal is composed of many arrivals and is spread in time. Peak pressure has little meaning for this messy arrival. The ESD versus frequency shows a more manageable picture. Here one can again observe the bubble repetition frequency and the relative level versus frequency. Transmission loss investigations often use the ESD to determine the TL versus range. In this example the ESD is expresser as an ESD Level dB re [(μPa)^2 s /Hz], the spectrum shown for the 24 m difference when corrected for spherical spreading becomes the EFSD Source Level dB re[(μPa)^2 s /Hz] @ 1 m.
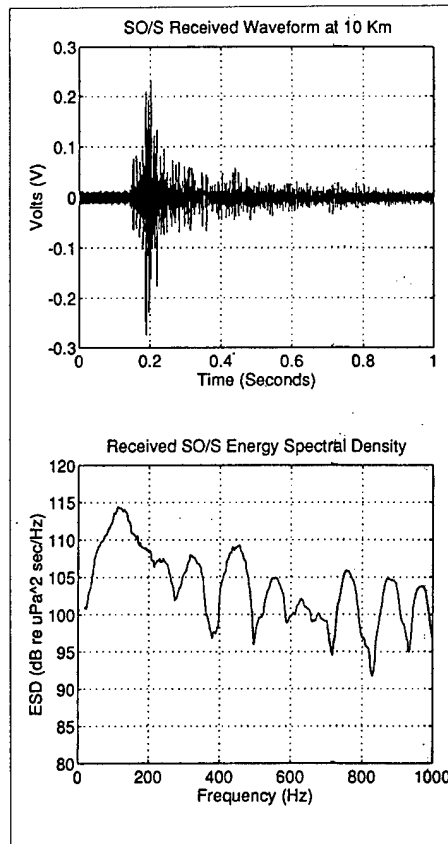
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Fig. 4; The pressure time series series and energy spectral density for the small omni explosive at a range of 10 km showing the importance of time spread. (Hydrophone sensitivity is -230 dB re (1 v/μPa)).

The explosive characteristics are:

Peak Pressure Level
$$PPL=Log ((p_p/\mu Pa)^{20})$$
PPL=233 Level relative to (μPa) @ 1 m;

Energy Flux Density Source Level
$$EFDSL=51 \text{ dB re } (mJ/m^2) @ 1 \text{ m};$$
$$EFDSL= 203 \text{ dB re } ((1\mu Pa)^2 \text{ -s}) @ 1 \text{ m}.$$

Impulse
$$I_{imp}= 4.5 \ 10^8 \ (\mu Pa\text{-s})$$

Another commonly used device is the air gun. These devices come in a large variety of sizes and can be used in arrays to increase source level. The unfortunate convention employed to classify air guns in terms of Bar-m or Pa-m will not be used here as these wave forms are energy waveforms and the above engineering notation confusing.. Peak pressures measured from air guns can range between 1 and 100 Pa at a reference distance of 1 meter. However these peak pressures are not the way to classify the waveform for studies other than seismic imaging.

Air guns are devices that use high pressure (> 2000 psi) to pressurize a chamber with a specified volume. A firing piston is then released and the pressurized air escapes through a port to form a rapidly expanding bubble. This rapid bubble expansion produces a shock wave followed by a pressure rarefaction due to bubble compression. This process then repeats at a repetition frequency determined by the bubble oscillation frequency. Thus the pressure, chamber volume and depth determine the radiated characteristics. Fig. 5 shows a collection of 40 air gun firings for a small 1/3 L gun operated at a pressure of 2000 psi and at a depth of 53 meters. The following characteristics were observed:

Peak Pressure Level
> PPL=236 Level relative to (μPa) @ 1 m;

Energy Flux Density Source Level
> EFDSL=71 dB re (mJ/m^2) @ 1 m;
> EFDSL= 228 dB re ((1μPa)^2 -s) @ 1 m.
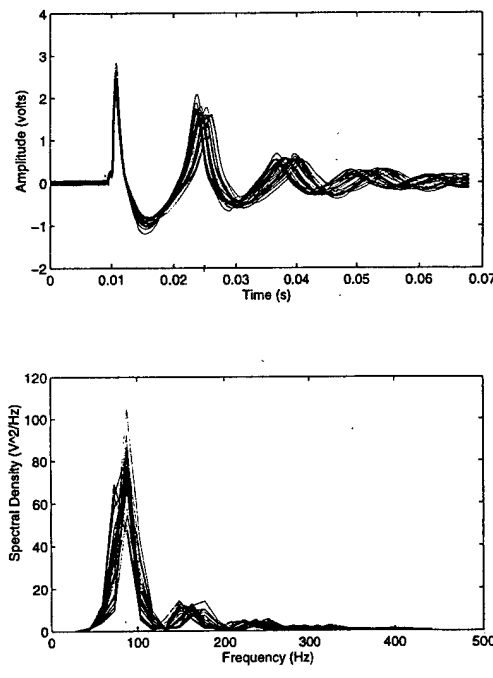
Impulse
> I_{imp}= 1.3 10^9 (μPa-s)

Fig. 5: Reproducible air gun signatures and a linear spectral density plot. The air gun had a volume of 1/3 liters, was driven with a 2000 psi pressure and was operated at a depth of 53 meters.(Effective sensitivity is -227.3 dB re((1 v/μPa)).

The effect of the oceanic waveguide is clearly shown in Fig. 6. One clearly observes the effect of the multi-path environment on the propagation of the above signal. The use of the energy spectral density function in transmission studies is adviseable. An example of the use of this type of device and that of a small omni explosive may be found in [35].
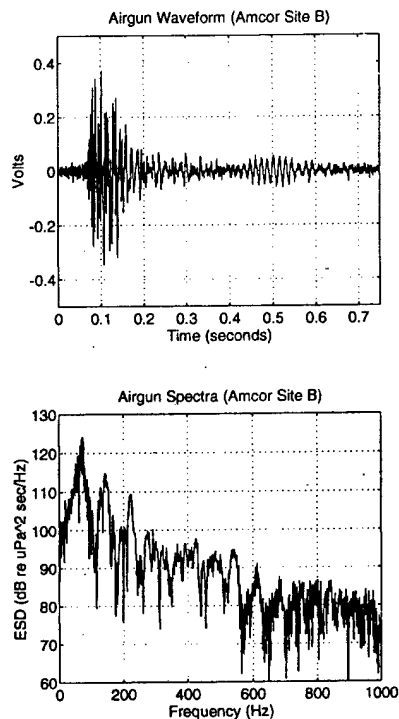
Fig. 6: The pressure time series and energy spectral density versus frequency at a range of 16 km on a vertical array in a water depth of 70 meters.

Another means of producing repoducible sound is by the use of glass spheres or light bulbs. Usually these bulbs are lowered to depth on a down-rigger with a weight. A sliding devive or a controlled hammer initiates the collapase-process. The total energy radiated is proportion to the PV work minus the effects of the surronding coated glass materials. Large spheres have been used to produce low frequency sound in the 50 Hz rang. The light bulb shown in Fig. 6 was imploded at a depth of 50 m in a water depth of 100 m. The range of the measurement was 200m. The second and smaller arrival is the sea surface and bottom reflections.

The following characteristics were observed in multiple bulb implosions at this depth.

Peak Pressure Level
    PPL=209 Level relative to (μPa) @ 1 m;
Energy Flux Density Source Level
    EFDSL=26 dB re (mJ/m^2) @ 1 m;
    EFDSL= 182 dB re ((1μPa)^2 -s) @ 1 m.
Impulse
    I_{imp}= 2.8 10^7 (μPa-s)

The final example of an impulsive wave form is the Dolphin click borrowed from Au [36]. This cliak has been compared to many different types of wave forms including air guns based on a peak pressure basis [4]. Figure 8 shows a single click from a pulse train of between 8-9 clicks per second.
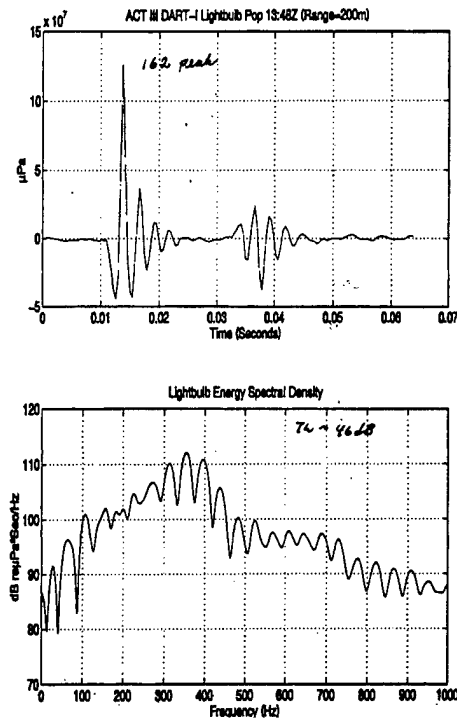
Fig. 7: The pressure time history and energy spectral density of an imploding light bulb at a range of 200 m,a depth of 50 m and water depth of 100m. The bulb was a 75 W Philips clear bulb.
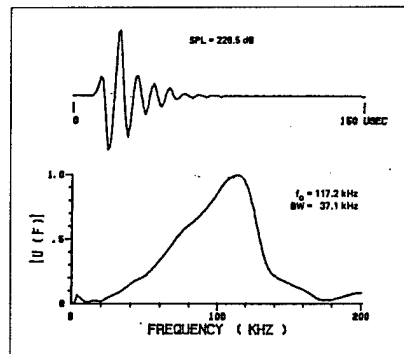

Fig. 8; An isolated Dolphin Click courtesy w. Au.[36].

The Peak Pressure Level is PPL= 226 re (1μPa) @1m with a center frequency of 117 kHz corresponding to a period T=8.5 μs, a T_e= 34 μs and T_R= 0.114 s. Using the definitions from Section II, one finds the following characteristics:

Peak Pressure Level
            PPL=226 Level relative to (μPa) @ 1 m;
Energy Flux Density Source Level
            EDSL=24 dB re (mJ/m^2) @ 1 m;
            EDSL= 170 dB re ((1μPa)^2 -s) @ 1 m.
Impulse
            I $_{imp}$= 1.8 10^6 (μPa-s)

Thus a meaningful comparison of source levels is summarized in the following table.

Table I: Comparative levels of a small explosive, air gun light bulb and a Dolphin click

PPL re (μPa)@1m	233	236	209	226
EFDSL dB re (mJ/m^2)@1m	51	71	26	24
EFDSL dB re ((μPa)^{2}s)@1m	203	228	182	176
I_{imp}(μPa s)	4.5 10^8	1.3 10^9	2.8 10^7	1.8 10^6

The comparison on the basis of peak pressure is meaningless especially when propagation is considered.

Table II Air gun and Dolphin click comparison

PPL re (μPa)@1m	226	226
EFDSL dB re (mJ/m^2)@1m	48	24
EFDSL dB re ((μPa)^{2}s)@1m	199	176
I_{imp}(μPa s)	2 10^8	1.8 10^6

If the peak pressure is the same between a Dolphin click and an air gun at lower frequencies, see Table II, all measures are dramatically larger for the lower frequency air gun as one would expect. The importance of correctly characterizing these different signals can not be understated. While it is not the purpose of this paper to specify parameters in environmental studies it is the purpose of this paper to stress appropriate metrics.

Biological wave forms are also of interest because of the variety and wide frequency range of these emissions. The basic metrics employed here apply to these waveforms but is beyond the scope of this paper; however, sonar system emissions are pertinent.

IV. A Simplified Model of Active Naval Sonar Systems:

The purpose of this section of the paper is to provide a simplified qualitative model of naval sonar systems useful in the estimation of pressure levels in the marine environment. The following summary and analysis is based solely on references available to the public at large. The purpose is to supply parameters to those concerned with the calculation of radiated sound fields, pressure levels, and the environmental impact.

Active sonar systems are described in reference [37] and are currently used by many of the world's navies. Common characteristics of these sonar systems are the utilization of time gated continuous wave (CW), frequency modulated (FM), and short time interval wide band (WB) pulses to perform sonar search, detection, and tracking, as well as collision avoidance. Typical bandwidths are 400 Hz for the FM pulses and 500-1000Hz for short duration pulses. Center frequencies range between 1 to 10 kHz. Sonar pulse repetition rates can vary depending on the application but in general these systems do not operate in a transmit / receive mode but rather in a synchronous "ping as you go" mode [6, 7, 37].

IV.1: Representative Source Levels

The actual source levels used in naval applications are largely unknown to the public; however, it is possible to place bounds on the performance of this type of system. The source level is related to the total radiated power of the source and is defined as the mean-square-sound-pressure level on the axis of the sound projector at a reference distance of 1 meter from the effective acoustical center of the projector. When the source is directional, Eq. 13, and the mean-square-pressure is measured on the principal axis of the transmitter in the far field at a fixed point, as shown in Fig. 9, and when this measurement is compared to an equal power omni-directional source, (i.e. the time-mean-square sound pressure over the surface of a sphere concentric with the effective center of the transducer and passing through the fixed point) then the ratio of the two determines the directivity factor. Ten times the logarithm to the base ten of the directivity factor is defined as the Directivity Index, DI. If SL_o is the source level of the omni-directional source and SL_d is the source level of the directional source then

$$SL_d \, [db \, re \, 1W] = SL_o \, [db \, re \, 1W] + DI. \tag{55}$$

Urick [7] has shown that when the reference is a mean square pressure of $(1 \, \mu P_a)^2$ that the source levels are related by the following :

$$SL_d \, [dB \, re \, 1W] = SL_o \, [dB \, re \, (1\mu Pa)^2] + DI - 170.77;$$
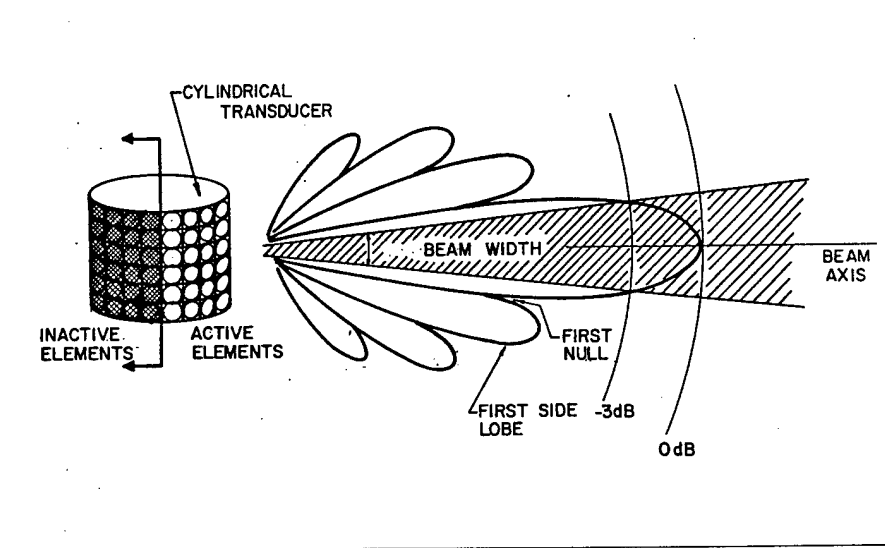$$when \quad \rho = 1000 \, kg/m^3 \, , \quad c = 1500 \, m/s. \tag{56}$$

Fig. 9: A typical surface ship sonar transmitter illustrating the main beam response axis, the beam width, and side lobe structure for rectangular shading.

Applying Eq. 54 to typical sonar parameters gleamed from the publicly available information [7, 37] the following performance metrics are derived:

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Transmitter Electrical Power:	$60 \text{ kW} < P_e < 90 \text{ kW}$
Transducer Efficiency:	$0.5 < E_e < 0.7$
Omni-directional SL_o (DI=0):	$216 < SL_o < 219$ [dB re μPa^2 @ 1m]
Directivity Index, DI:	$10 < DI < 30$ dB
Directional SL_D:	$226 < SL_d < 248$
Peak Omni Pressure:	$6.1 \cdot 10^{10} < P_{op} < 8.9 \cdot 10^{10} \ \mu P_a$
Peak Directional Pressure:	$2 \cdot 10^{11} < P_{dp} < 2.5 \cdot 10^{12} \ \mu P_a$
Omni-directional Intensity:	$1.26 \cdot 10^3 < I_o < 2.6 \cdot 10^5 \text{ W/m}^2$
Peak Intensity:	$1.32 \cdot 10^4 < I_d < 2.1 \cdot 10^6 \text{ W/m}^2$

There is considerable variation in the above parameters so it is necessary to refine these estimates with information from reference [37] and physical considerations. Modern active sonar systems are limited by the onset of cavitation and/or the mutual-transmitter-element interaction. The cavitation limit is the important factor for surface-ship sonar and Urick [7] states that the cavitation threshold can be estimated by the threshold at the surface of the sea modified by the depth effect. The cavitation pressure can be written as

$$P_{AC}(z)[atm] = P_{AC}(z)[atm] + z(m)/10.06[m/atm] = 1 + T + z/10.06, \qquad (57)$$

where T is the tensile strength of the fluid in atmosphere. The equivalent plane wave intensity corresponding to this cavitation threshold would be

$$I_{TC} = <I> = <p^2> /2\rho c = p_{rms}^2 /\rho c = 3.33 \cdot 10^3 \ (P_{Ac}(atm))^2 ,[W/m^2]. \qquad (58)$$

At frequencies less than 25 kHz, the cavitation threshold is relatively independent of frequency. Estimates for the cavitation threshold of Castor Oil [7, 37-41], a commonly used transducer oil, range between 4 atm and 5.3 atm; a threshold of 5 atm is used following [7]. Typical near the surface sonar transmitters are at a depth of ~6 m and can be pressurized to a depth of ~ 9 m. Thus the cavitation threshold under these conditions is between $5.06 \cdot 10^5 \ P_a$ and $6.29 \cdot 10^5 \ P_a$. The calculation is performed as follows:

The cavitation threshold intensity:	$I_c \ [W/m^2] = 3.33 \cdot 10^{-7} \ p_c \ (P_a)^2$.
The total transducer power:	$P_t = I_c \cdot A_t$ with $A_t \sim 1.863 \cdot 10^{-2} \ m^2$
The transducer source Intensity:	$I_s(1m) = P_t/4\pi = I_c \cdot A_t/4\pi = 4.94 \cdot 10^{-10} p_c^2 \ [W/m^2]$.
The source intensity ratio sl:	$sl = I_s(1m)/I_{ref} \ (1m, 1\mu P_a) = 1.48 \cdot 10^{-3} [p_c/p_{ref}] \ 2$
The element Source Level:	SL_e [dB re μPa^2 @ 1m] $= 10 Log \ (sl)$
	$= -28.29 + 10 \ Log \ ([p_c/p_{ref}] \ 2)$
	with $p_{ref} = 1\mu P_a$ and $p_c = 6.29 \cdot 10^{11} \mu P_a$;
	$\underline{SL_e = 207.6 \ [dB \ re \ \mu Pa^2 @ 1m]}.$

The directivity due to the horizontal and vertical array extent must also be considered. If the transmit array has Hann shaded elements to reduce side lobes, then an array with 8 vertical- and 24 horizontal-transmitter elements produces a directivity as shown in Fig. 9. . The directional gains are:

Vertical: $DI_v = 20 \text{ Log } (2N_{vc}/3) = 14.5 \text{ dB}$,
Source Level: $SL_v = SLe + DI_v = 222 \text{ [dB re } \mu Pa^2 @ 1m]$,
Horizontal: $DI_h = 20 \text{ Log } (2N_{hc}/3) = 24.1 \text{ dB}$,
Source Level $SL = SLe + DI_v + DI_h = 246 \text{ [dB re } \mu Pa^2 @ 1m]$.

These source levels are representative limits for near surface sonar transmitters and most operational systems should operate at lesser levels by as much as 10 dB.

IV.2: Typical System Characteristics [7, 37].

The shape and size of a sonar array is determined by its application. Most surface ship active sonar arrays are cylindrical since a rapid scan in the horizontal over nearly 360° is desirable. The vertical extent of the array is primarily to optimize the use of the sonar in surface duct, convergence zone (CZ) and bottom bounce (BB) modes. The vertical beamforming is usually directed at 0° horizontal, ± 12.5° (CZ) and ± 25° (BB). Modern sonar systems may be more selective but for our application the above information should suffice for the computation of the sound field. Spherical arrays such as those found on submarines are employed when continuous coverage in the horizontal and vertical is required. The modern day submarine sonar [37] can have 10 elevation angle between =19° and −53° with 6° x 7.2° half power beam widths, Hpbws. In submarine applications the mutual element interaction limits the source level and is difficult to estimate, the parameters for the surface ship sonar systems are used.

Table III. Sonar System Parameters [37]

Sonar System[2]	Frequency/BW	Source Level Limit	Hpbw	Waveform
SQS 23/SQQ23	4.5-5 kHz/400	244 dB	10°x15°	CW-LFM-WB
BQQ5/BQQ6	3.5 kHz/400	unknown	6° x 7°	CW-LFM
SQS53/SQS26	3.5 kHZ/400,1k	246dB	5°x14°	CW-LFM-WB
SQS56	6.7-8.4,7.5/400	252 dB	5°x14°	CW-LFM-WB

In the vertical direction, an array with a length between 5 and 10λ seems representative based on photographs of actual systems. A useful rule of thumb for estimating the parameters to be used in the farfield calculations can be found in [42] and results tabulated below.

Table IV. Sonar Shading Characteristics [42]

Shading	SLL_{maz}	Gain	B.W.	Hpbw	$Hpbw \cdot (L/\lambda)$
Rectangular	-13 dB	1.00	1.00	0.89	$50.8° \sec\theta$
Hann- cos(x)	-23	0.64	1.23	1.20	$64.8° \sec\theta$
Gaussian-exp(-(2.5x/4)^2)	-42	0.51	1.39	1.33	$76.9° \sec\theta$

The source levels and beam widths used in this paper correspond to a Hann shaded array. However these parameters can be estimated by using a Gaussian shaded array whose properties are matched to the Hann shaded case by changing the factor of 2.5 in the expression for the Gaussian function listed in the above table. A Gaussian shading of elements produces a Gaussian beam and is a useful starting field for computation.

In summary, the directionality of an active sonar based on a vertical aperture of between 4-10λ for a shaded array matched to Gaussian beam provides a useful initial field for both Parabolic Equation, PE, and ray-trace methods.

IV.3: Pulse Duration and Repetition Rates:

The repetition rate of the sonar depends on the operational application and these characteristics are generally not available. However, the openly advertised applications [36] of active sonar are: a.) deep water (DW), convergence zone (CZ), bottom bounce (BB) and surface duct (SD) search and track and b.) shallow water (SW) search, track and mine avoidance. For these applications, order of magnitude estimates can be readily made by simply using estimated round trip travel times based on depth averaged sound speed with ranges determine either by a one way loss <100 dB or the presence of a feature [7, pp154-155, fig.6.26]. The transmitted signals can be interleaved provided a range window around the max range is specified. The key variable is that the received signal arrives after the reverberation of the most recent transmission has been reduced. Although the times listed below may not be those actually used by the world's navies, these estimates should provide the right order of magnitude. It is important to stress that the repetition rate is selectable and coupled to the pulse type, duration, size of the object being searched and speed of advance.

Table V. Estimated Repetition Rates

Deep Water (DW)	R(nmi/km)	ΔT_{rt}	Single Pulse	Sync Pulse
CZ	35/65	86s	0.5s	→2 ppm
BB	<20/37	49	1.0	→3 ppm
SD	≤5/9	12	5.0	10 ppm
Shallow Water				
DP	~11/20	13	2.5	3→5 ppm
MA	1.9/2	2	45	≥45 ppm

In summary, deep water sound propagation from an active sonar system using CW/FM pulses of 1-2 second duration, a representative repetition rate greater than 1ppm but less than 10 ppm while for the SW mine avoidance problem the repetition rate can be greater than 45 ppm.

IV.4: Summary of Typical Surface-Ship Sonar Characteristics:

A simplified surface-ship sonar model useful in performing environmental assessments has been developed. Fig. 9 shows the beam pattern and along axis response which can be interpreted with the following generic parameters:

General Array characteristics
Height, $L_v = 4\lambda$, $N_e = 8$.

Effective Horizontal Length, $L_h = 10\lambda$, $N_{he} = 24$.

Omni Directional Source Level
$SL_o = 230\, dB\, re\, 1\mu Pa\, @\, 1m\, for\, frequency\, of\, 3.5kHz.$

Gaussian Track Beam
Half Power Beam Width = 7°.

Source Level for the Track Beam, Main Response Axis
$SL_d = 246\, dB\, re\, 1\mu Pa\, @\, 1m\, for\, a\, frequency\, of\, 3.5\, kHz.$

Pulses:
CW: 1-2 secs., Band Width, BW = 0.5 Hz.
FM: 1-2 secs., BW= 100-400 Hz.
Chirp:10 msec., BW= 1000 Hz.

Repetition Rates
DW-CZ	0.5 to 2 ppm
DW-BB	3 ppm
SD	1 to 10 ppm
SW -ASW	3 to 5 ppm
SW-MA	≥ 45 ppm

These metrics can be applied to a specific pulsing scheme to characterize the waveform and subsequently the source level and energy flux density for the sonar. One should differentiate between the short and long duration sounds. The key objective would be clarity in calculating the source levels and levels at distance that consider the peak pressure, the energy flux density and the time average intensity.

IV.5: Near Field Effects

Two near field effects are important because of the rapid fluctuation of field quantities. The first is due to the aperture itself. The distance to the nth element of an array along the z axis to a point R at angle θ to the normal to the array is

$$L_N = R[1 + 2Z_N \sin(\theta)/R + (Z_N/R)^2]^{1/2} \qquad (59)$$

Using a standard expansion one finds

$$L_N \cong R + Z_N \sin(\theta) + Z_N^2 \cos(\theta)^2/2R \qquad (60)$$

="direct"+ "steering"+ "focusing".

Each term when multiplied by the wave number k can be related to phase observed at the distance R from the array and the farfield can be defined when the "focusing" term is small:

$$kZ_N^2 \cos(\theta)^2 / 2R \leq \pi / 4, \quad \theta = 0, \ Z_N = L/2 \tag{61}$$

$$\rightarrow R_{ff} \geq L^2 / \lambda$$

Thus a simple rule of thumb is that the farfield is reached when the observation point R is greater than the array length squared divided by the wavelength. The field is calculable along its axis and Fig. 10 illustrates this effect for $\theta=0$. For the generic system presented here one has $R_{V,ff} \approx 7M$ AND $R_{H,ff} = 42M$.
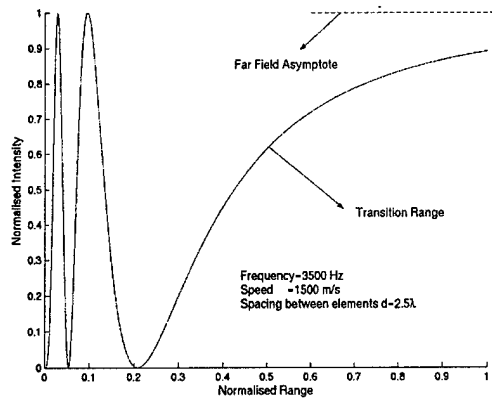

Figure 10: The near field interference pattern for a 4 element array with a 2.5 λ spacing at a frequency of 3,500 Hz.

The second effect is the Lloyd Mirror or surface image interference effect. The geometry is shown in Fig. 11 for a point source below the pressure release surface.
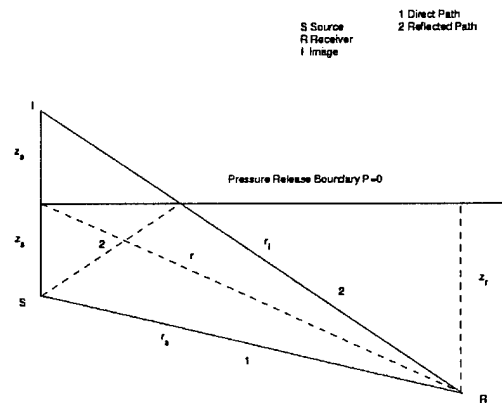

Fig. 11: The Lloyd Mirror Geometry

The image effect can quite easily be derived by summing the pressure from the source and its image multiplied by a roughness parameter μ:

$$p[r,t] = p_s[r_s,t] + p_i[r_i,t] \qquad (62)$$

The distance from the source, r_s, and the image, r_i, can be written:

$$r_{s,i} = [r^2 + (z_r \pm z_{s,i})^2]^{1/2}. \qquad (63)$$

Assuming spherical waves one has with a reflection coefficient

$$\mu = \mu_o \exp[-2(kh\sin\theta_g)^2] \qquad (64)$$

and the superposition of pressures

$$p[r,t] = p_s[r_s,t] + p_i[r_i,t]$$
$$= [p_{os}/r_s] \cdot \exp[ikr_s - i\omega t] + [\mu p_{os}/r_i] \cdot \exp[ikr_i - i\omega t]. \qquad (65)$$

$$\rightarrow p[r,t] = [p_{os}/r] \cdot \exp[ikr - i\omega t] \cdot [\exp(-ikz_s z_r/r) + \mu\exp(ikz_s z_r/r)].$$

The intensity can be calculated with a little algebra

$$I = (1/2\rho c)\operatorname{Re}(pp^*) = (p_{os}^2/2\rho c) \cdot [1/r^2] \cdot [1 + \mu^2 + 2\mu\cos(2kz_r z_s/r)]. \qquad (66)$$

This equation can be re written as

$$I = I_{os}[1/r^2] \cdot [1 + \mu^2 + 2\mu(1 - 2\sin(kz_r z_s/r)^2]$$
$$\rightarrow \mu = -1 \rightarrow I_{os}[1/r^2] \cdot [4\sin(kz_r z_s/r)^2]. \qquad (67)$$

Finally one has an expression for the intensity variation versus range.

$$10Log(I/I_{os}) = -20Log(r) + 10Log(4) + 20Log(kz_r z_s/r) = -TL \qquad (68)$$

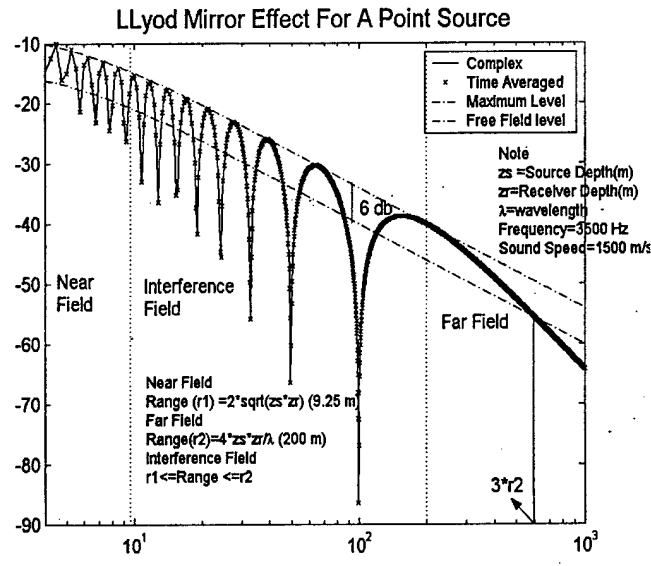This variation is shown in Fig. 12 where the near, interference and far fields are shown.

Figure 12: The Lloyd Mirror effect for a near surface source as a function of range. Specifically these regions can be summarized as follows for the Lloyd Mirror, surface image interference effect;

near field $\qquad\qquad R_{NF} \leq [2Z_S Z_r]^{1/2}$

30

$$\text{far field} \qquad R_{FF} \geq 4Z_S Z_r / \lambda$$
$$\text{interference field} \qquad R_{NF} \leq R \leq R_{FF}$$

The combination of this point source effect and the presence of a distributed array beneath the surface can easily be calculated by the superposition of pressures.

V Summary and Conclusions

This paper has stressed the use of Sysstem Internation units and the use of decible levels to provide clarity to the problem of describing sound levels in the ocean. First the definition of the decibel from the nationsl standard is the logaritm of a ratio proportional to power

$$dB \equiv Log_{10^{1/10}}(PR) = 10 \cdot Log_{10}(PR).$$

This paper recommends that a simple convention be used to clarify the use of levels:

$$L_{xxx} \, dB \, re \, xxx \quad or \quad xxx \, Level \, dB \, re \, xxx.$$

That is the label and the reference units should match a summary is

Sound Pressure Level
SPL= 10 Log[<p^2>/<μPa^2>], dB re (μPa)^2

Energy Flux Density Level
$$EFDSL = 10 \, Log_{10}[E / E_{ref}], \, dB \, re \, ((1\mu Pa^2) \cdot (1s)) @ 1 meter.$$

$$EFDSL = 10 \, Log_{10}[E / E_{ref}], \, dB \, re \, (1J / m^2) @ 1 meter.$$

Energy Spectral Density level
$$ESDL = 10 \cdot Log(E(1Hz \, band) / ((1\mu Pa)^2 \cdot s / Hz))$$

Sound Exposure Level
$$SEL = 10 \cdot Log_{10}[E_x / E_{xref}], \, dB \, re \, (1J / m^2).$$

Power spectral Density Level
$$PSDL \equiv 10 \cdot Log_{10}[W_p \, (f)_T / W_{p,ref}(f)_T], dB \, re \, (1W / m^2 Hz)$$

$$= 10 \cdot Log_{10}[(< p^2(t) >_{NT} / \Delta f) / < p_{ref}^2 > / \Delta f_{ref}] \; ; dB \, re \, (\mu Pa)^2 / Hz).$$

Source Levels with the 1 m Convention
Pressure Source Level
$$PSL = 10 \cdot Log(< p^2 > / < p_{ref}^2 >) , \quad dB \, re \, (\mu Pa)^2 @ 1m.$$

Intensity Source Level
$$ISL = 10 \cdot Log(I / I_{ref}), \, dB \, re \, (W / m^2)$$

Power Radiated Source Level
$$P_{rad} SL = 10 \cdot Log(P / P_{ref}), dB \, re \, (1W)$$

An added means of clarity is to also list the actual pressure, intensity, power, and energy with the appropriate SI unit. This paper has stressed sound sources pertinent to the Oceanic Engineering community who out of necessity need to satisfy both societal as well as engineering concerns.

A key point of this paper is to stress the characterization of a sound source depends on whether it is continuous, transient of shot duration, or a longer duration sonar pulse. Repetition rate is also a metric that is required. Example of these sources were presented and discussed. A simplified generic model of surface-ship active-sonar system was presented based on an open literature survey to expedite calculations necessary for environmental assessments.

Finally this paper does present new facts but simply applies standard definitions to the problem at hand to clarify a current engineering and societal problem.

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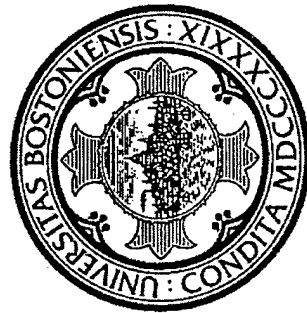
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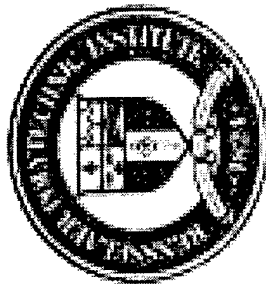
The application of standard definitions of sound to the fields of underwater acoustics and acoustical oceanography

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147th Meeting of the Acoustical Society of America
New York, New York
24 May 2004

NAVSEA
NEWPORT
Undersea Warfare Center Division

UNIVERSITAS BOSTONIENSIS : XIXXXI : CONDITA MDCCC

WOODS HOLE OCEANOGRAPHIC INSTITUTION
1930

What is the role of standards in the Underwater Acoustics and Acoustical Oceanographic Communities ?

- This question is really a statement of the problem facing us today!

- The question concerns at a minimum the committees of Acoustical Oceanography, Animal Bioacoustics, Engineering Acoustics, Signal Processing and Underwater Acoustics.

- The requirement is "Communication" in standard scientific terminology.

This paper recommends the application of current standards with SI Metric references specified. Clarity is the objective.

Standards apply in several areas

Units, symbols, and terminology

- Spectral density of the above
- Metric specification of pressure, velocity, energy and power.
- Symbols to specify quantities and levels
- Definition of reference quantities and levels

Calibration Techniques

- Primary Calibrations
- Secondary calibrations

"*When is a μPa really a μPa ?*"

Measurement and Survey Techniques

- How is the measurement calibrated and specified.

Analysis and Computational Techniques

- Specification of computational output-the observable.

Recommendation

- *Traceable calibration is a necessity.*

- *Measurements an calculations should use SI units and clearly defined observables.*

- *The reference quantities for level determination should match the level modifier.* (*Power Level dB re 1 W, Intensity Level dB re 1 W/m^2, Pressure Level dB re (1 μPa))*

- *The SI units should be specified: 10 dB re 1 W, (10 Watts)*

The Rule Should Be Clarity!

The Current Problem:

Can you perform an experiment without harming marine life?

- ## Continuous and long duration pulses

  - Source Level

  - Power Spectral Density of the Source Level

  - Pressure and Intensity Field versus Range and Depth

- ## Transient and short duration pulses

  - Near the source

    - Peak Pressure, duration, Energy Spectral density

    - Energy Flux Density Source Level

  - At a distance from source (>several water depths)

    - Time spread and Energy Spectral Density

    - CDF of peak pressures in range depth cells.

    - Energy Spectral Density as a function of Range and Depth

WHAT IS A DECIBEL?
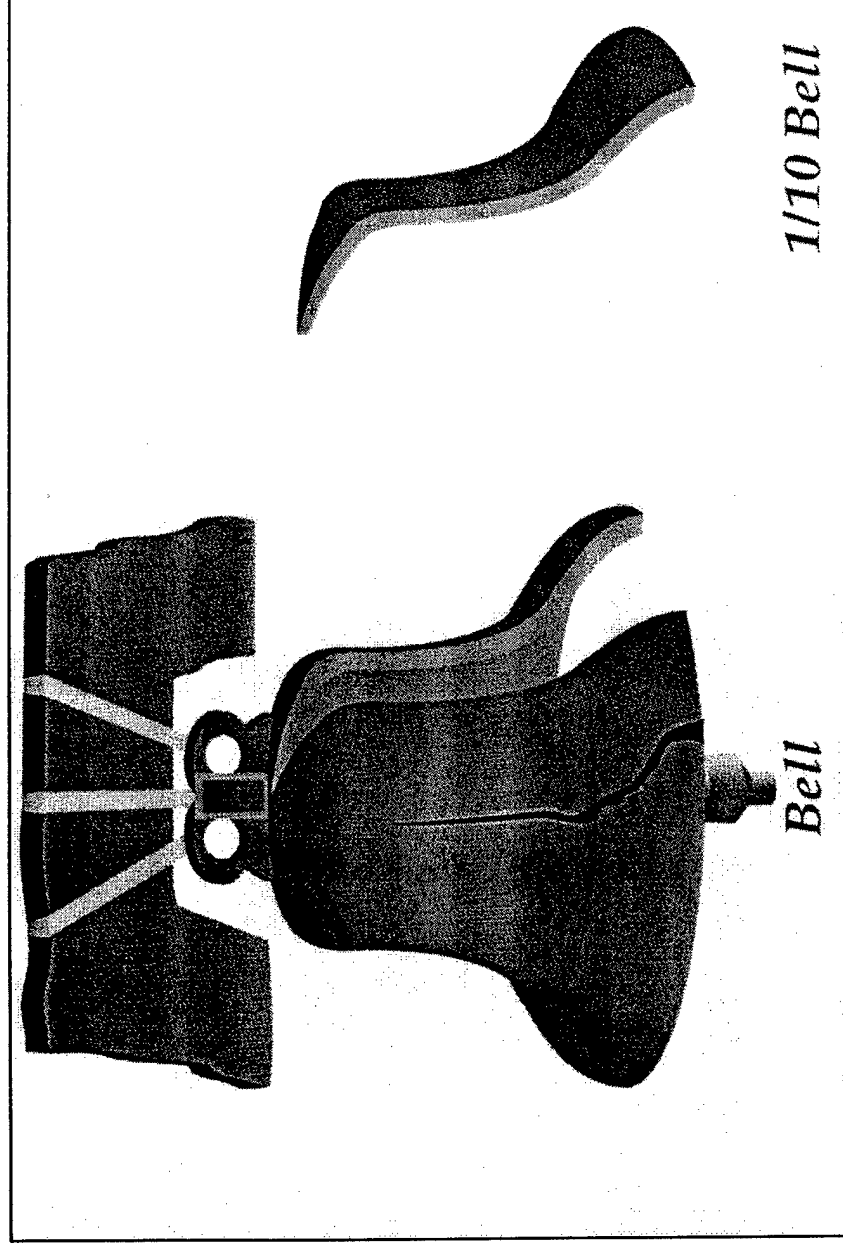
1/10 Bell

Bell

The Bewildering Decibel an interesting story!

The Bewildering Decibel- An Interesting History

(See A. Pierce, Acoustics, ASA,1991)

- **Fletcher('23)** –Bell System-Sensation unit, $10^{0.1}$, or an incremental change of 0.1 on a $Log_{10}(<p_2^2>/<p_1^2>)$ scale.

- **Hartley ('24) and Martin ('29)**– The transmission unit ($10^{0.1}$) and the decibel ($10 Log_{10}$(Power Ratio)).

- **1924-Int'l Advisory Com. on Long Distance Telephony**

   "To Recommend Standards and practices"

   - Basic Power Ratio is e^2, the neper- Napier
   - Basic Power Ratio is 10^1, the bel- A. G. Bell

   The Bell System adopted the " decibel" for the "transmission unit" or a power ratio = $10^{0.1}$ with the "deci" indicating the $1/10^{th}$ relation.

- **Knudsen('29)**was the first to the dB use in the Journal.

R. V. L. Hartley, "The Transmission Unit", Elec. Commun. 3(1), 34-42, 1924; W. H. Martin, "Decibel-The Name for the Transmission Unit", The Bell Sustem Technical Journal, New York, N.Y., 8(1), 1-2, 1929; V. O. Knudsen, "The Hearing of Speech in Auditoriums," J. Acoust. Soc. Am. 1, 56-

The Bewildering Decibel- An Interesting History "Underwater Sound"

- **Leonardo da Vinci (1490)** *" If you cause your ship to stop and place the head of a long tube in the water and the other extremity to your ear, you will hear ships at a great distance from you"*

- **WW I (1918)**– *British scientist improve this device by using two tubes to make the sound reception binaural.*

- **WW II (1946)** - *NDRC Div. 6- Under J. Tate - C. Eckart and L. Spitzer-First use of a sonar equation to govern rapid R&D.*

SE=SL-TL-NL +AG +PG+DT

This enabled the division of labor with consistent results provided each referenced his results to 1 yd and used dB's with appropriate reference quantities.

References supplied upon request

The Bewildering Decibel- An Interesting History "Underwater Sound", However...

IRE (1952) : This is a reminder of the admonitions of the I.R.E. Standards Committee in 1952 [11]:

"Which two values of power are meant when a standing-wave ratio is expressed in decibels? Which two values of power are meant when a television signal-noise ratio is expressed in decibels? Which two values of power are meant when the contrast range of a picture is expressed in decibels? Can you figure out what is meant when the statistical variance of a quantity, no matter what it is, is expressed in decibels? In short, have you noticed the meaning of decibel is being extended to a point of real ambiguity?

The Standards Committee of the Institute finds it so. The practice is so widespread that it is guardedly admitted in standard definitions, including some recently published by the IRE. Such official concession confuses rather than clarifies the issue."
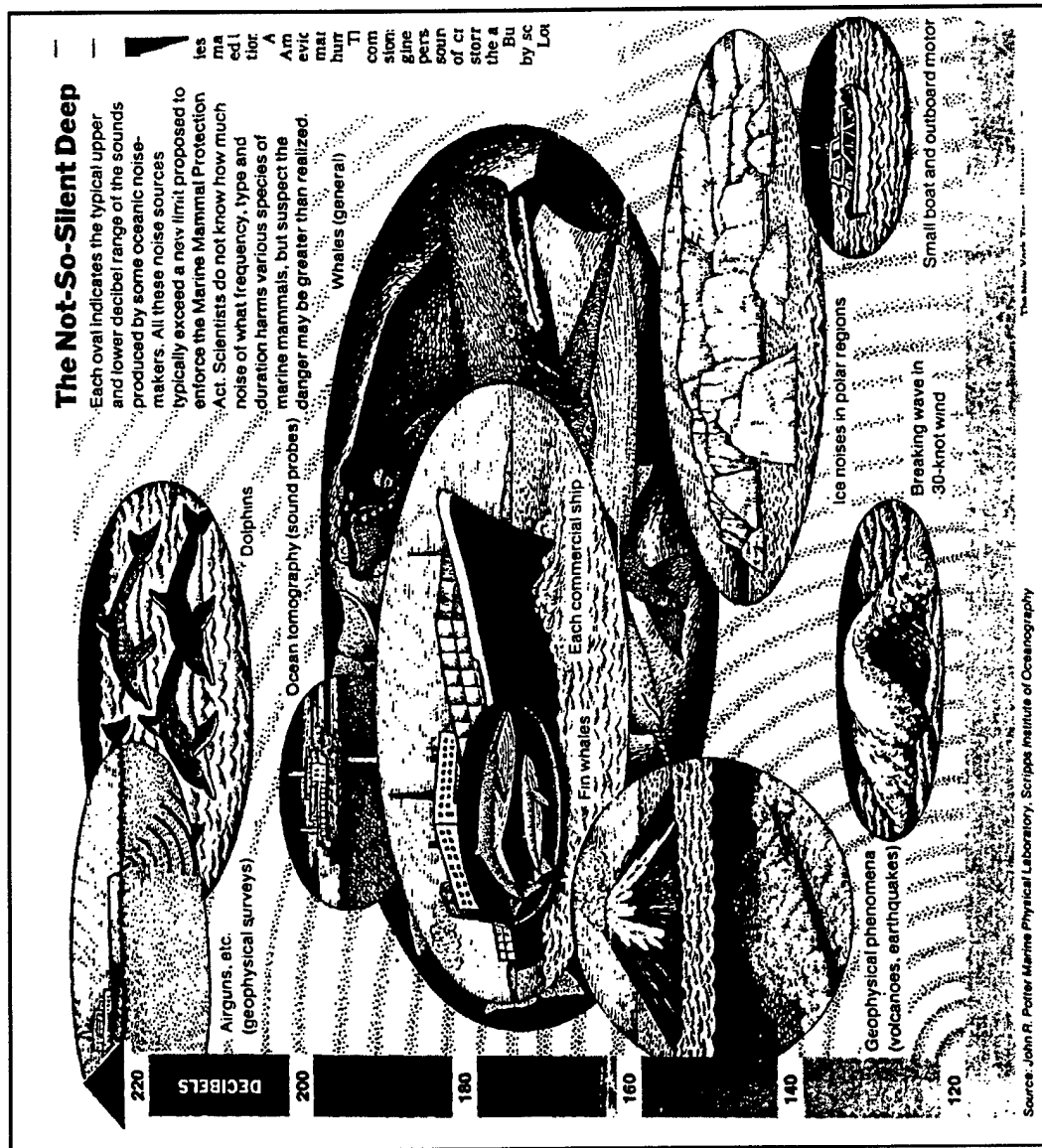
—These views were ignored.

Preface to J. W. Horton, "The Bewildering Decibel," Elec. Eng., Vol. 73, no. 6, pp. 550-555, June 1954.

The Bewildering Decibel- An Interesting History" Underwater Sound", However Recently

- 126th Meeting of the Acoustical Society of America , Oceans 93, and Oceans 94.

- National Research Council (1994), NRC, monograph "Low-Frequency Sound and Marine Mammals" , This monograph may not have clarified the issue due to the use of mixed conventions, units, and measures (peak, root mean square, and square values) irrespective of frequency and bandwidth.

- NRC 2000, "Marine Mammals and Low-Frequency Sound Progress Since 1994"

These meetings and reports have problems wit the use of SI Metric Units and Decibel Levels. Never mind the use of correct reference quantities!

The Not-So-Silent Deep

Each oval indicates the typical upper and lower decibel range of the sounds produced by some oceanic noise-makers. All these noise sources typically exceed a new limit proposed to enforce the Marine Mammal Protection Act. Scientists do not know how much noise of what frequency, type and duration harms various species of marine mammals, but suspect the danger may be greater than realized.

Whales (general)

Dolphins

Airguns, etc. (geophysical surveys)

Ocean tomography (sound probes)

Fin whales

Each commercial ship

Geophysical phenomena (volcanoes, earthquakes)

Ice noises in polar regions

Breaking wave in 30-knot wind

Small boat and outboard motor

DECIBELS

220 200 180 160 140 120

Source: John R. Potter Marine Physical Laboratory, Scripps Institute of Oceanography

The discussions and papers presented at the 126th Meeting of the Acoustical Society of America [1], Oceans 93 [2], and Oceans 94 [5] illustrated the confusion with respect to the application of national standards to the characterization of sound source levels

Bahamas Marine Mammal Stranding Event of 15-16 March 2000
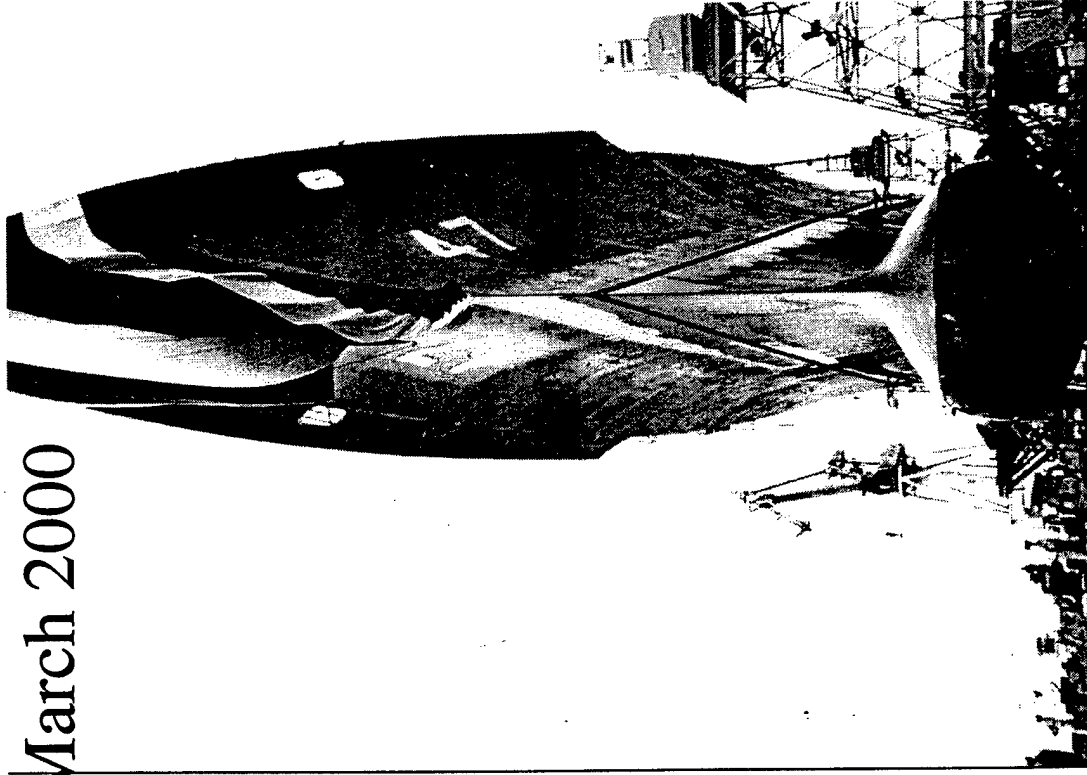
The most recent application of the decibel concerns the stranding of marine mammals in the Bahamas during a naval exercise in 2000.

This stranding was of societal concern and subsequently the Department of Commerce, D. Evans, and the Department of the Navy, G. England conducted an exhaustive and expensive evaluation of this incidence.

However, even though these departments have access to talented scientists, they did not use the current standards rather they redefined the decibel and terms of the sonar equation

" Joint Interim Report Bahamas Marine Mammal Stranding Event of 15-16 March 2000."

- *"DeciBel (dB): Decibel is a dimensionless ratio term that can be applied to any two values; temperature, rainfall, the number of jellybeans in a jar, or sound. Decibels are expressed as 10 times the logarithm of the ratio of a value (V) to its reference value (Vref), or: N decibels (dB) = 10*log (V/Vref) The decibel originated in electrical engineering measurements of transmission line losses, but it is also physiologically significant in that the response of biological ears to sound is logarithmic. Decibels should always be accompanied by a reference value that defines the ratio being expressed, unless the reference is clearly stated at the start of the paper."*

D. L. Evans, Sec. the Dept. of Commerce, G.R. England, Sec. of the Navy, C.C. Lautenbacher Jr. Under Sec. for Oceans and Atmosphere, S. M. Livingstone, Under Sec. of the Navy, W. T. Hograth Assit. Admin. National Marine Fisheries service. Sec. of the Navy, 2001, "Joint Interim Report Bahamas Marine Mammal Stranding Event of 15-16 March 2000."

What is a Level?

- A _LEVEL_ IN ACOUSTICS IS THE LOGARITHM OF A RATIO !

$$LEVEL \equiv LOG(R)$$

- A _BEL_ IS A UNIT OF LEVEL WHEN THE BASE IS TEN AND R IS A RATIO OF POWERS.
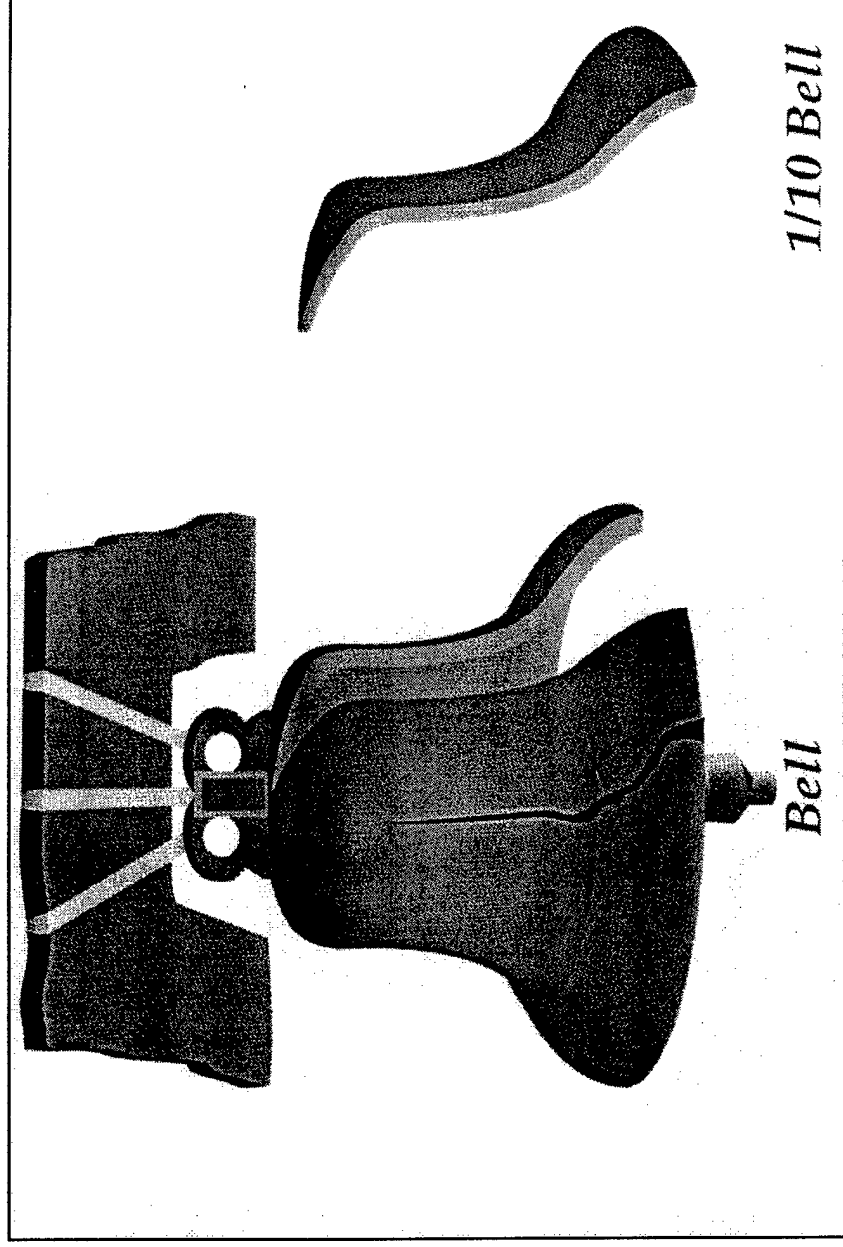
$$BEL \equiv LOG_{10}(PR)$$

- A _DECIBEL_ (dB) IS ONE TENTH OF A BEL.

$$dB \equiv LOG_{10}1/10(PR) = 10LOG(PR)$$

- THE _NEPER_ IS A UNIT OF LEVEL WHEN THE LOGARITHM IS ON THE NAPIERIAN BASE e.

WHAT IS A DECIBEL?--WHO CARES?
THE NAVY SHOULD!

Bell

1/10 Bell

THE GOAL IS TO SPECIFY QUANTITIES ACCORDING TO AMERICAN NATIONAL STANDARDS AND TERMINOLOGY; USE SI METRIC; AS WELL AS LEVELS, dB, FOR POWER AND ENERGY SIGNALS.

A level convention

(XXXXXX) LEVEL dB re $[U_x]$

EXAMPLES

SOUND PRESSURE LEVEL dB re $[1\mu Pa]$

POWER SPECTRAL DENSITY LEVEL dB re $[W/Hz]$

INTENSITY SPECTRUM LEVEL dB re $[W/(m^2 Hz)]$

ASSUMING $I = P^2/2\rho c$

PRESSURE SPECTRUM LEVEL dB re $[(1\mu Pa)^2/Hz]$

ENERGY FLUX SPECTRAL DENSITY LEVEL dB re $[J/(m^2 Hz)]$

OR EFSDL dB re $[(1\mu Pa)^2 s/Hz]$

Standard Definitions of the Field

- **The Pressure:**

$$P(R,t) = (Q_s / R) \cdot \sin(\omega(t - R/c)), \; [\, P_a = N/m^2 \,].$$

- **The Particle Velocity:**

$$U(R,t) = (Q_s / \rho c R) \sin(\omega(t - R/c)) + (Q_s / k\rho c R^2) \cos(\omega(t - R/c))$$

$$\rightarrow ff \rightarrow = (Q_s / \rho c R) \sin(\omega(t - R/c)), \; [m/s].$$

- **The Instantaneous Intensity:**

$$I(R,t) = U(R,t) \cdot P(R,t) = (Q_s^2 / \rho c R^2) \sin(\omega(t - R/c))^2, \; [W/m^2]$$

$$= (Q_s^2 / \rho c R^2) \cdot (1 - \cos(2\omega(t - R/c))).$$

The Source Level

• <u>*THE CONTINOUS SOURCE:*</u>

$I(R) = Q_S^2 / 2\rho c R^2 \rightarrow R = 1m \rightarrow I(1m) = Q_S^2 / 2\rho c, \ W/m^2$

THE SOURCE LEVEL: $\ SL = 10LOG(I(1m)/I_{ref})$,

when $I_{ref} = 1W/m^2 \ $ *then* $SL(\ dB \ re \ 1W/m^2 \ @ \ 1 \ m) \ $ *and*

when $I_{ref} = (1/2\rho c)\cdot(1\mu Pa)^2 \ $ *then* $SL(\ dB \ re \ (1\mu Pa)^2 @ \ 1 \ m)$

RIGHT CYLINDRICAL ARRAY

BEAM PATTERN NOMENCLATURE
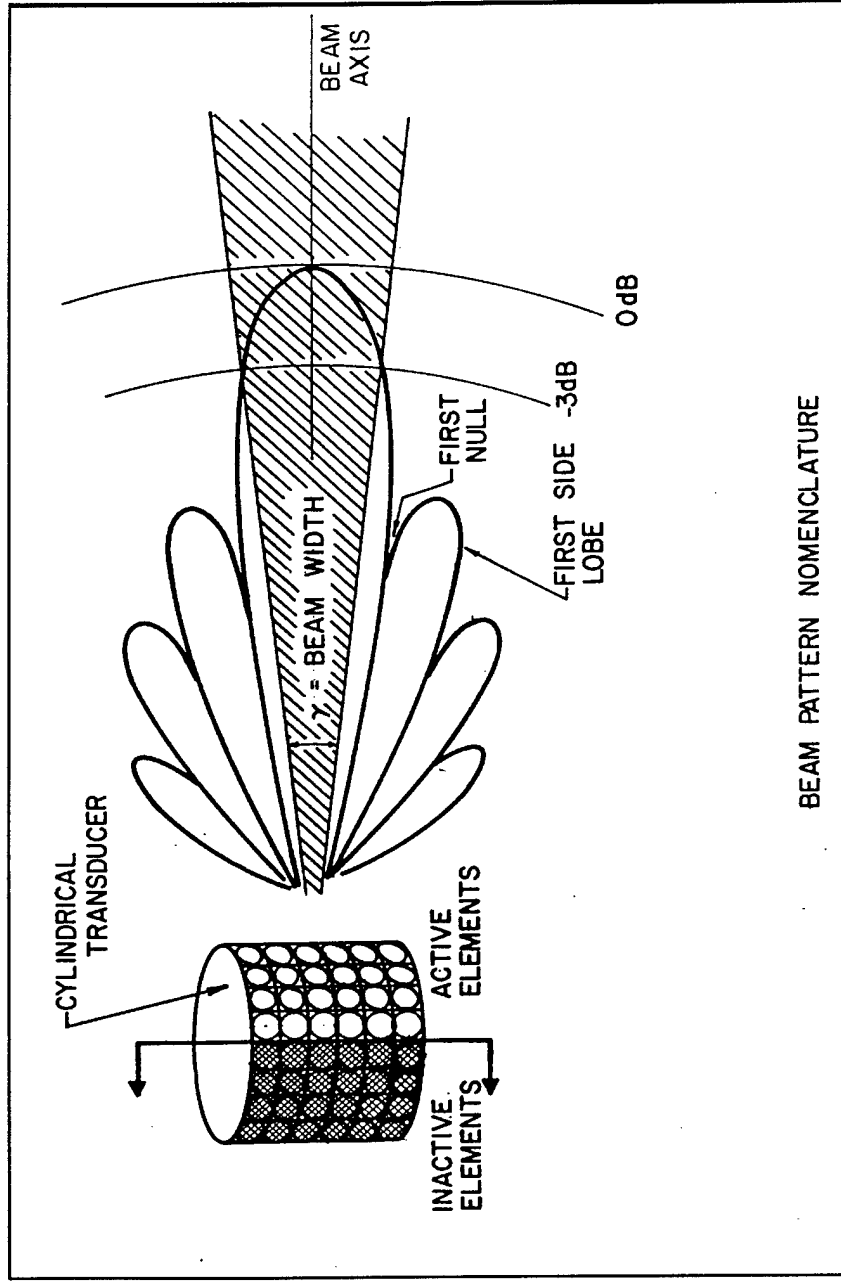
The ATOC Source Characteristic

- BW = 20 Hz
- Band Level: 195 dB re 1μPa @ 1m
- SPL @ 70 Hz = 195dB - 10 LOG(BW)
  = 182 dB re (1μPa)^2/Hz
- Duty Cycle = 8 %
- f_c = 20 Hz
- T_t = 20 min

(195 dB ref μPA)

Linear Voltage Response (Q=4)

Freq in Hz

Pt. Sur ATOC source bandlimited M-sequence
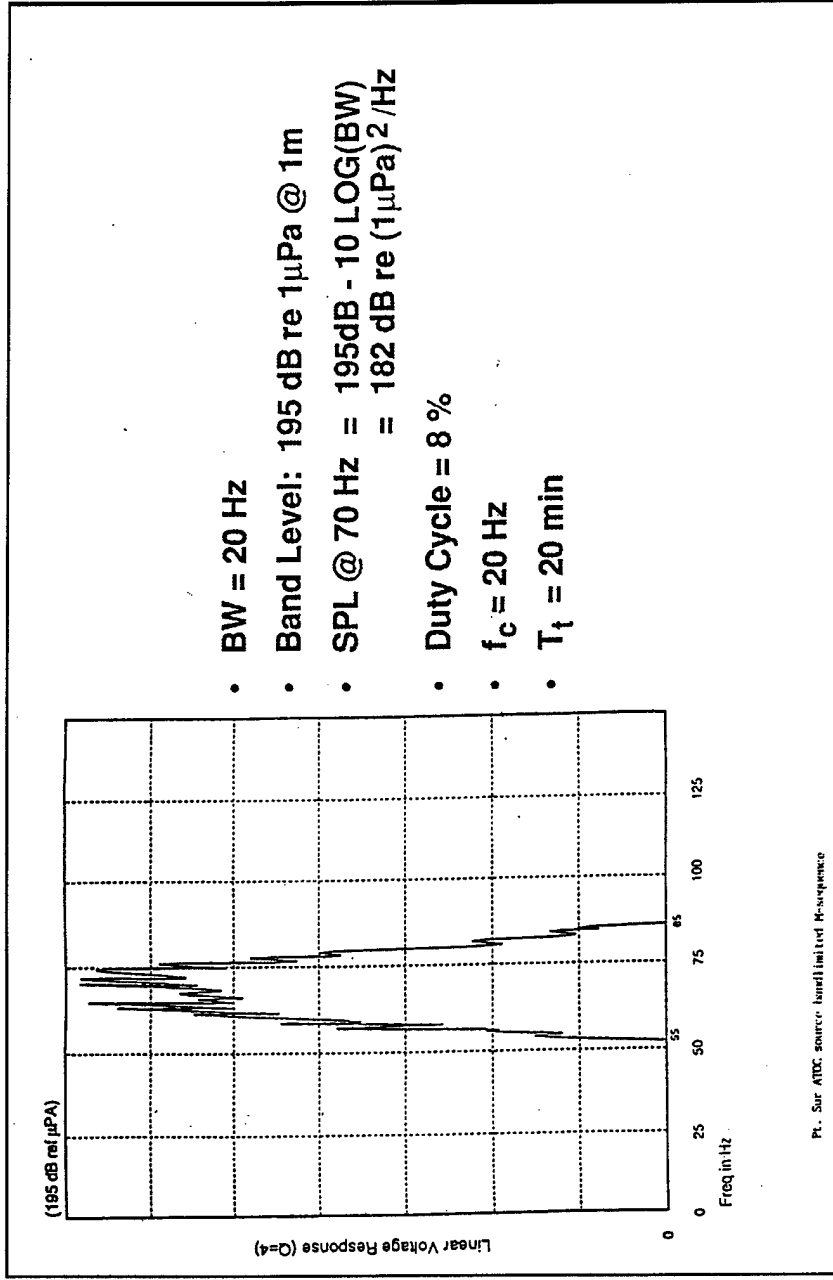
The Extremes in the Events of the Day in the Life of a Near Bottom Hydrophone
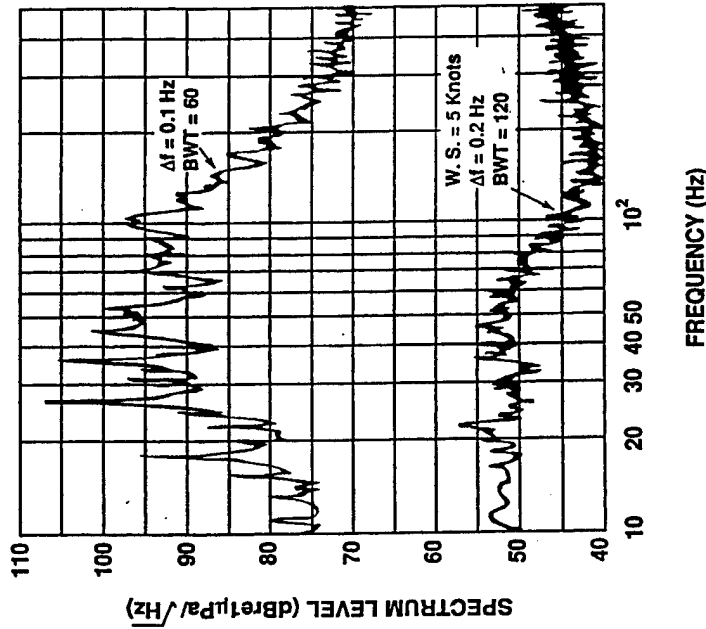
$$SPL = SL - TL = SL - 20LOG(R)$$
$$= SL - 74 \ dB.$$

THE LEVEL AT 26 Hz IS

$$SL = 170 \ dB \ re \ \mu Pa^2 \ @ \ 1m.$$

NOTE: $I / \Delta f \ \left[W / m^2 - Hz \right]$,

$$I / \Delta f \propto P^2 / \Delta f \ \left[\mu Pa^2 / Hz \right]$$

$$\propto \left(P^2 / \Delta f \right) \cdot \left[\mu Pa / \sqrt{Hz} \right]^2$$

SPECTRUM LEVEL (dBre1µPa/Hz)

FREQUENCY (Hz)

Δf = 0.1 Hz
BWT = 60

W. S. = 5 Knots
Δf = 0.2 Hz
BWT = 120

- 12,000 TON JAPANESE FREIGHTER PASSING 4,850 METERS OVER THE HYDROPHONE. ALSO SHOWN IS THE AMBIENT NOISE FOR A 5 KNOT WIND SPEED.

Transient Waveforms

Instantaneous Intensity: $\quad I(r,t) = P(t)^2 / \rho cr \to I(1,t) = P(t)^2 / \rho c$

Time Averaged Intensity: $\quad \langle I(1,t) \rangle = [1/T] \int_0^T I(1,t)dt$

But $T = T_t + T_r$ where $I = 0$ when $t > T_t$ And $\langle I \rangle \to 0$ as $T \to \infty$

However Energy of a Transient is finite: $\quad E_t = \int_0^{T_{tt}} I(1,t)dt = I_t \cdot T_t$

Energy Flux Density $[J/m^2] = E_t = T_t I_t$

and $\langle I \rangle / I_{ref} = (T_t/T_{ref}) I_t/I_{ref} = [E_t/T]/[E_{ref}/T_{ref}]$

Thus for short time transient wave forms we use E!

Transient waveform relations

Gated CW

$$E = P_o^2 T_p / 2\rho c \quad I_{av} = [P_o^2 / 2\rho c] \cdot [T_p / T_R] \quad I_{imp} \approx P_o T_o / \pi$$

Exponential

$$E = P_o^2 T_e / 2\rho c \quad I_{av} = [P_o^2 / 2\rho c] \cdot [T_e / T_R] \quad I_{imp} = P_o T_e$$

Damped Sinusoid

$$E = P_o^2 T_e / 4\rho c \quad I_{av} = [P_o^2 / 4\rho c] \cdot [T_e / T_R] \quad I_{imp} \approx P_o T_o / 2\pi$$
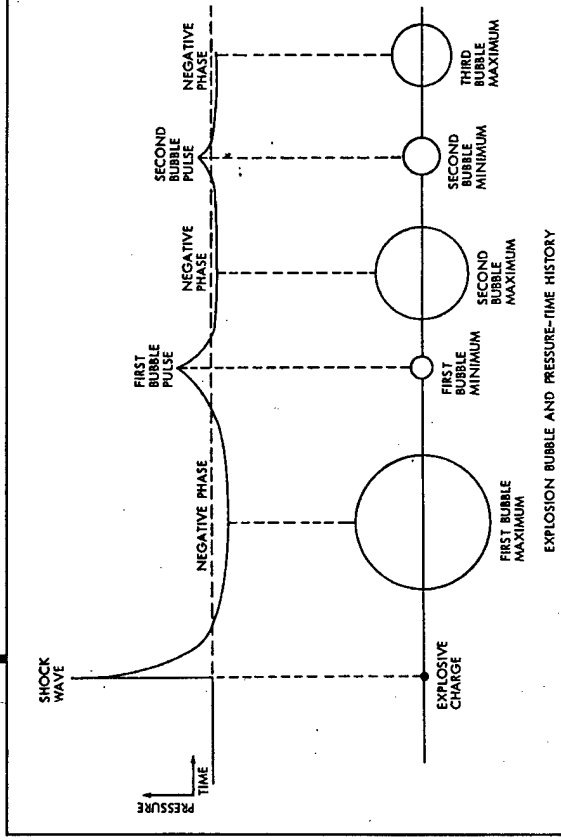
$$I_{imp} = P_o T_o [1 + \exp(-T_o / 2T_e)] / 2\pi(1 + (T_o / 2\pi T_e)^2)$$

These are the parameters necessary to characterize a short time pulse.

Examples of Transient, "Energy", Wave Forms"

- The Small Omni-directional Explosive

- The Air Gun

- The Light Bulb Source
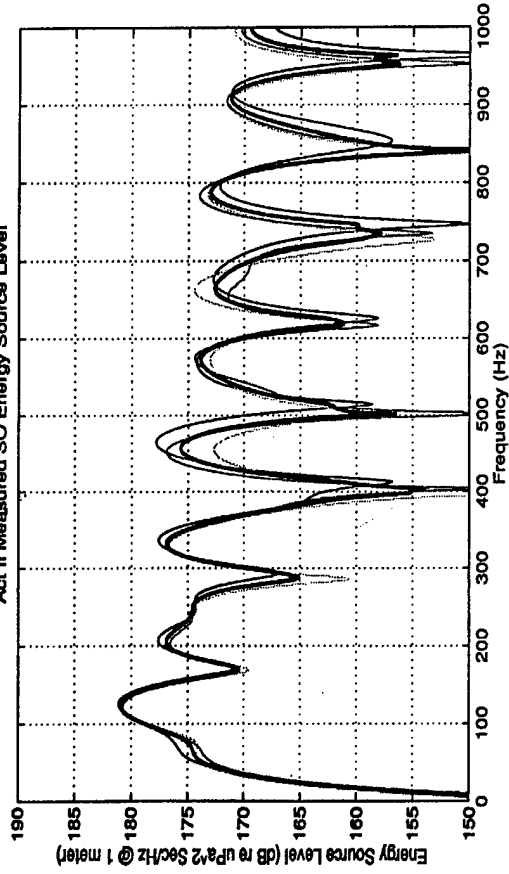
- Biological Sounds

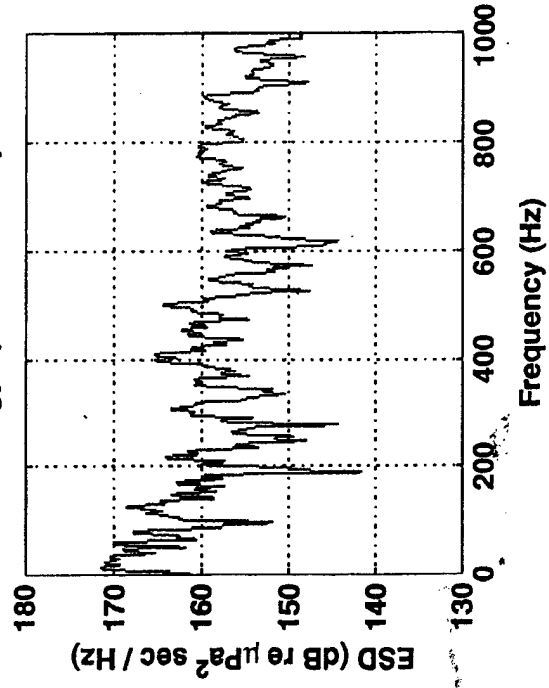- The Echo Location Click
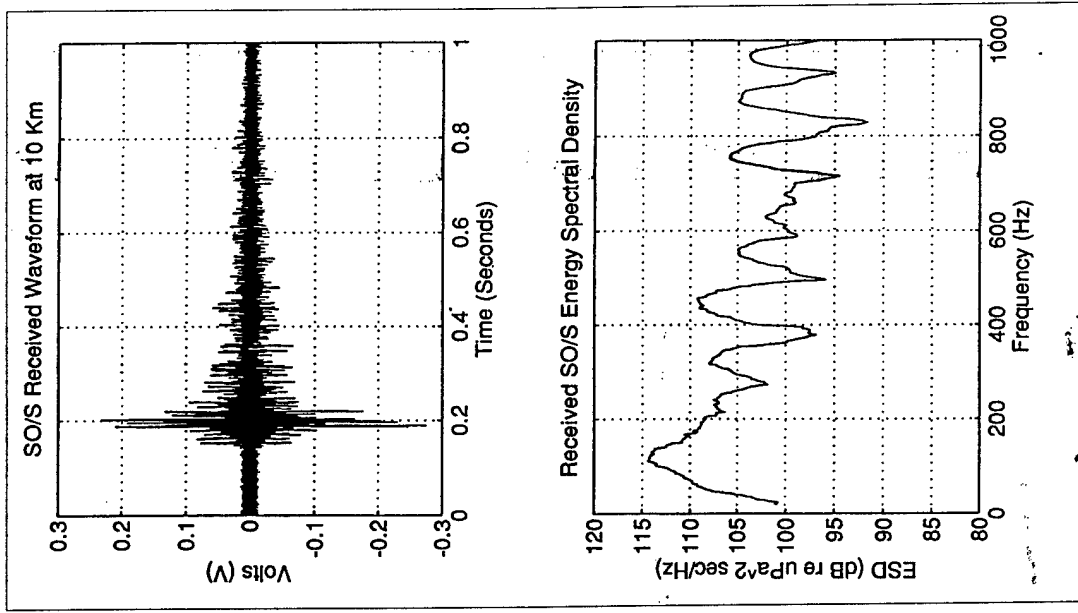
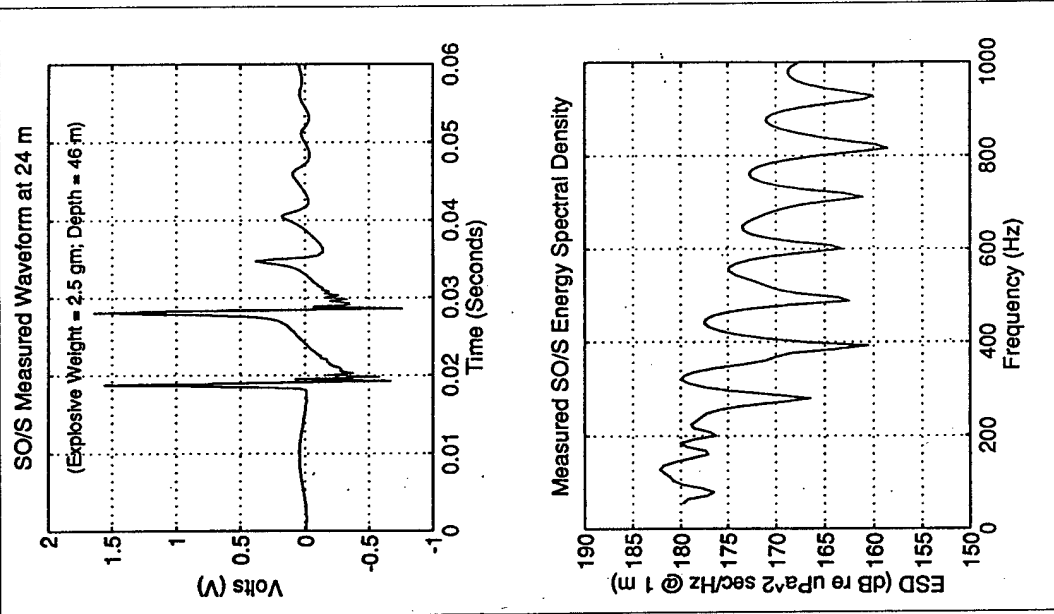# An Explosive Source

Explosive Waveform at 290 m

(Weight = 1.81 kg; Depth = 45 m)

Volts (V)

Time (seconds)

Energy Spectral Density

ESD (dB re µPa² sec / Hz)

Frequency (Hz)

EXPLOSION BUBBLE AND PRESSURE-TIME HISTORY

SHOCK WAVE

NEGATIVE PHASE

FIRST BUBBLE PULSE

NEGATIVE PHASE

SECOND BUBBLE PULSE

NEGATIVE PHASE

THIRD BUBBLE MAXIMUM

SECOND BUBBLE MINIMUM

SECOND BUBBLE MAXIMUM

FIRST BUBBLE MINIMUM

FIRST BUBBLE MAXIMUM

EXPLOSIVE CHARGE

PRESSURE

TIME

Act II Measured SO Energy Source Level

Energy Source Level (dB re uPa^2 Sec/Hz @ 1 meter)

Frequency (Hz)

SO/S Received Waveform at 10 Km

SO/S Measured Waveform at 24 m
(Explosive Weight = 2.5 gm; Depth = 46 m)

Received SO/S Energy Spectral Density

Measured SO/S Energy Spectral Density

The Air Gun
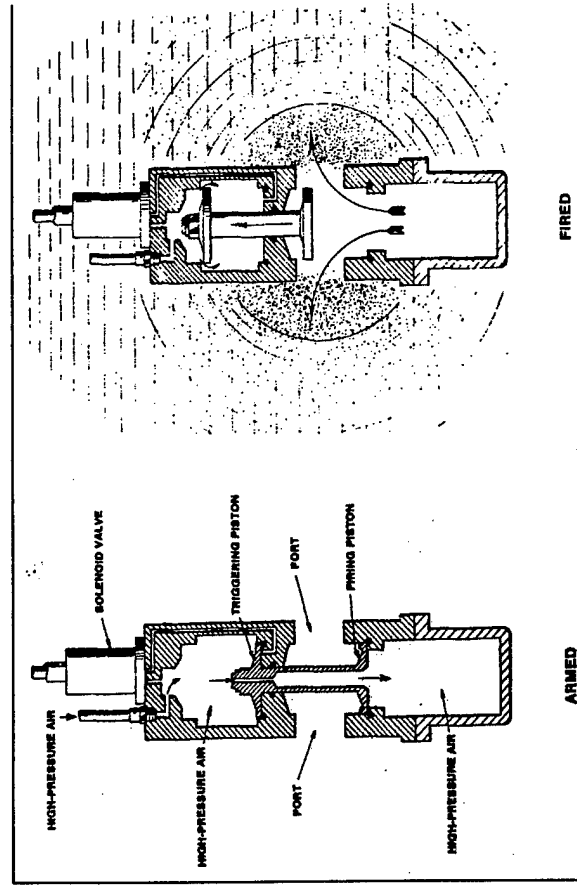

Airgun Waveform (Amcor Site B)
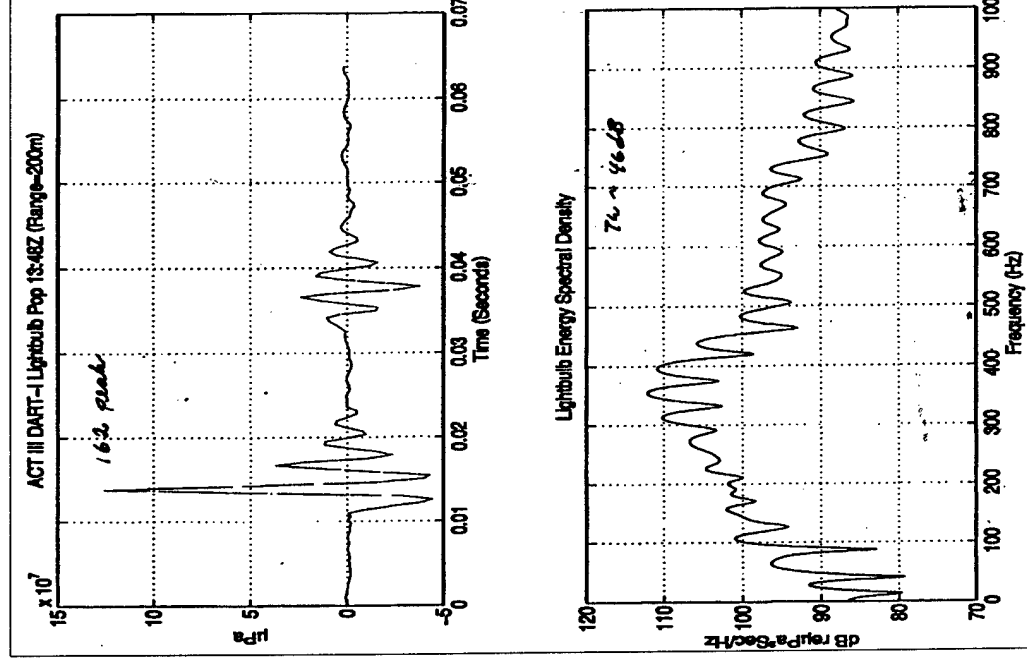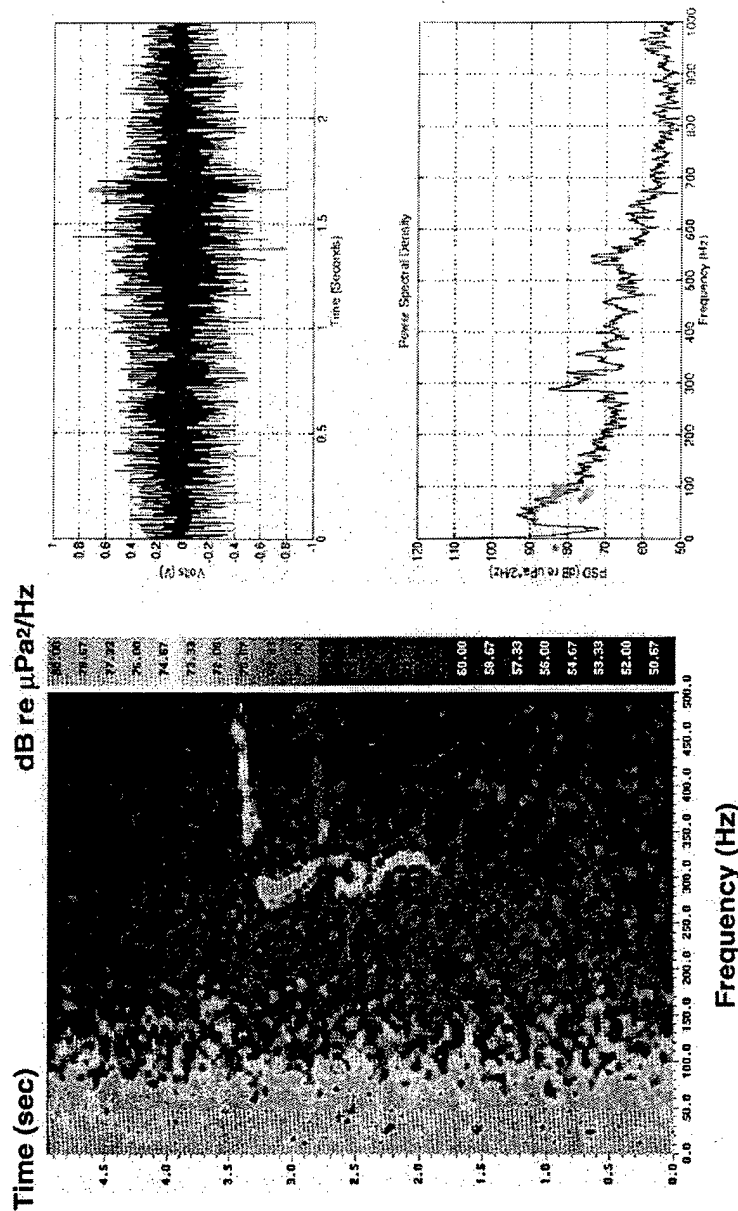
Airgun Spectra (Amcor Site B)

ARMED

FIRED
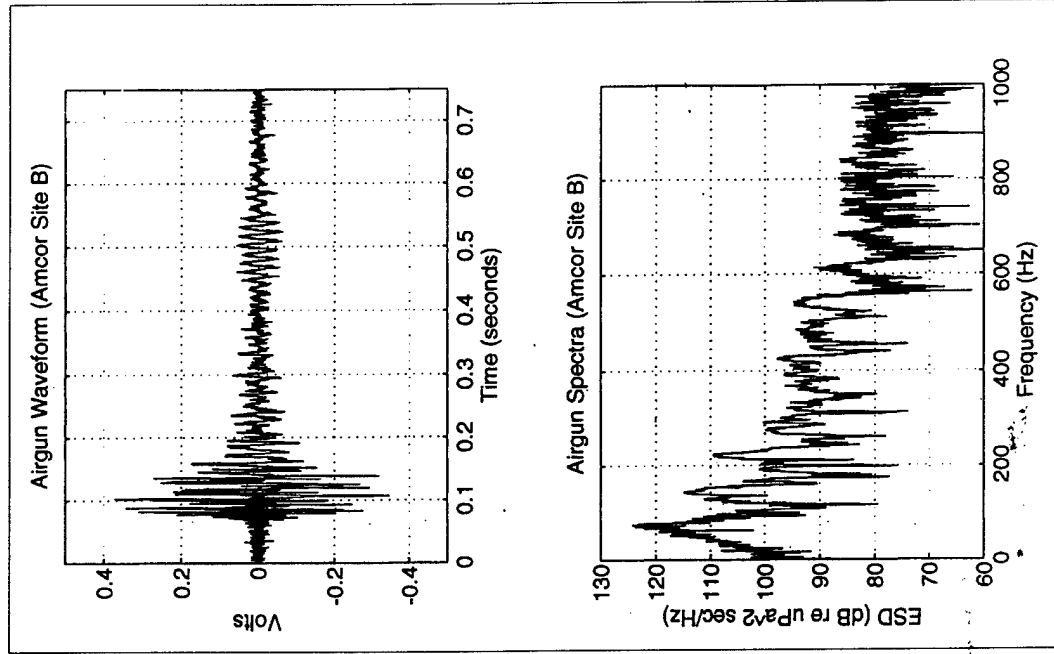
The Light Bulb Sound Source

To Obtain Energy Flux
Density Source Level add 46
dB to the ordinate.

Biologic Waveform #1
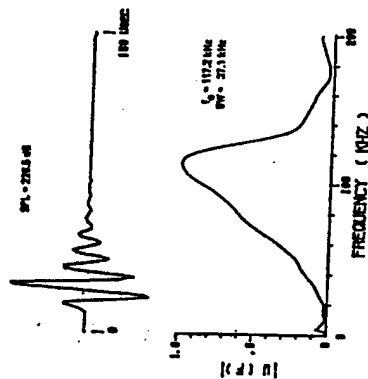
Echolocation Clicks After Au

Figure 2. The averaged waveform and spectrum for the click train of Fig. 1.

$$SPL = 226.5dB \ re \ 1\mu Pa$$

$$P_o^2 = 4.4668 \cdot 10^{22} (\mu Pa)^2, f_o = 117.2 \ kHz,$$

$$t_o = 8.532 \cdot 10^{-6} s, \ t_e = 4 \cdot t_o$$

$$E = P_o^2 t_e / 4\rho c = 0.2467 J / m^2, \ T_R = 3.65/32$$

$$I_{av} = E / T_R = 2.1627 \ W / m^2$$

$$SPL = 226.5 \ dB .... ISL = 188dB \ re \ (\mu Pa)^2$$

$$EFSL = 169 \ dB \ re \ \left((\mu Pa)^2 - s \right)$$

Calibration

- ## The Underwater Sound Reference Division

    [Dr. Joe Zalesack and A. L. Van Buren]

- ## Survey Systems

    - Resolution, Source level , Calibration Targets

- *Should the national organization responsible for underwater acoustic standards and references be in a naval system command?*

UNDERWATER ACOUSTIC METROLOGY

NAVSEA
NEWPORT
Undersea Warfare Center Division

- **US standardization** in underwater acoustic measurements is provided by the **Underwater Sound Reference Division (USRD)** of the Naval Undersea Warfare Center Division Newport.

- **USRD**
  - was established as part of WWII effort
  - became an ONR Laboratory in 1946
  - Consolidated under NRL in 1966
  - Transferred to NUWC Division Newport in 1995
 - Relocated to Newport RI as part of BRAC95

UNDERWATER SOUND REFERENCE DIVISION (USRD)

- Provides acoustic calibration, test, and evaluation reference measurements

- Recognized by the National Institute of Standards and Technology (NIST) as the equivalent to NIST in underwater acoustic measurements

- Serves as the Principal Navy and US expert in the theory and practice of underwater electroacoustic measurements

- Establishes the US National standards for underwater electroacoustic measurements

- Maintains an inventory of secondary transducer standards for use by the Navy, its contractors, and other approved activities

UNDERWATER SOUND REFERENCE DIVISION (USRD)

- Operates six facilities that provide calibration, test, and evaluation measurements on acoustic transducers and materials for the Navy, its contractors, and other US activities.

- These facilities provide a wide range of water temperatures and hydrostatic pressures to simulate realistic operational conditions.

- In addition to the USRD facilities, NUWC operates the Seneca Lake Facility to provide measurements on very large devices or those that require large distances in deep water.

- NUWC also operates the Acoustic Test Facility, a large open water tank with high precision positioning required for measurements including wave-field scanning at higher frequencies.

Transducer Standards Loan Program
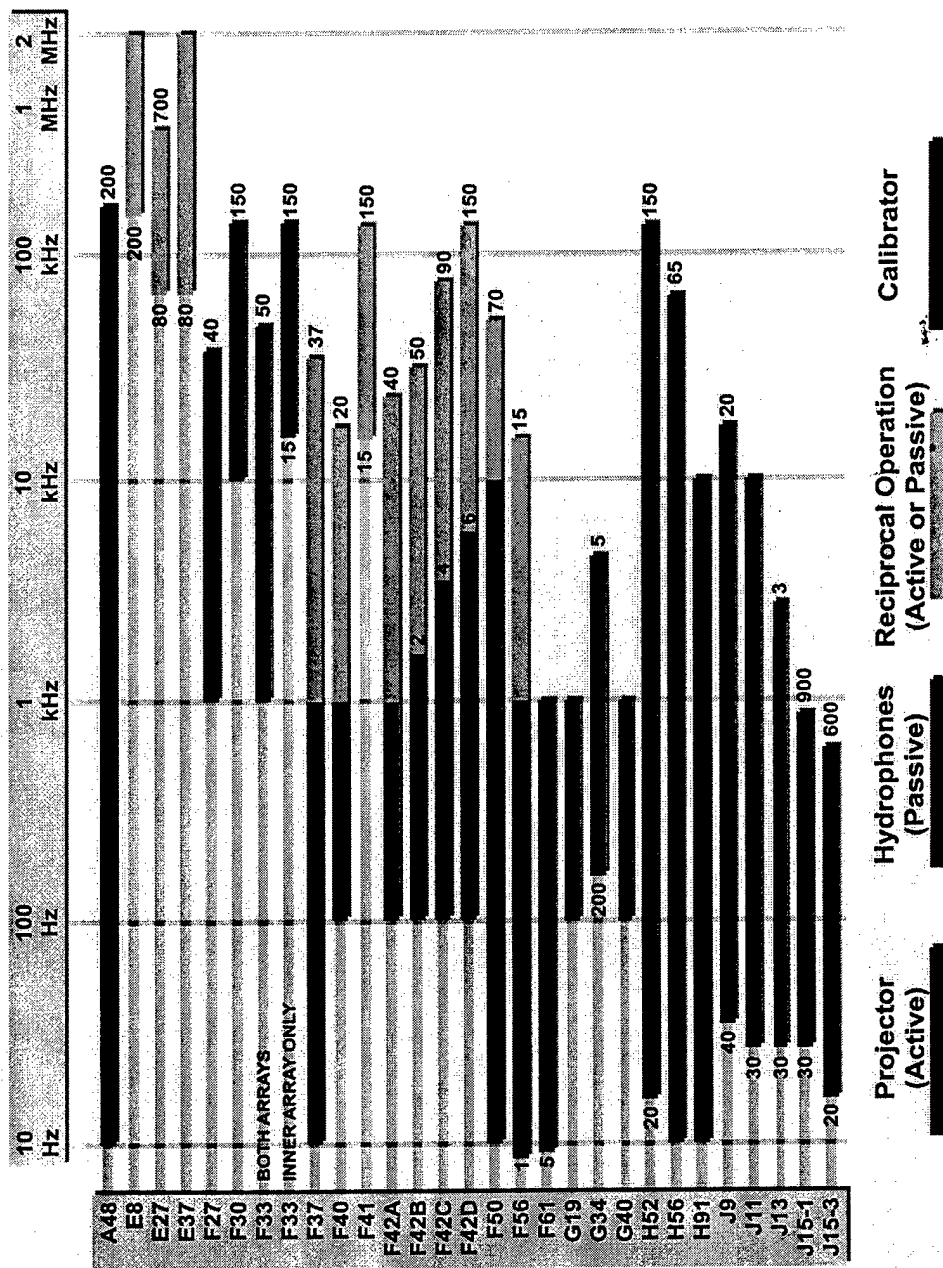
Transducer Standards Loan Program

- Loan hydrophones and reciprocal transducers (when used as a hydrophone) are US national secondary standards with traceability to NIST

- Provides a wide range of calibrated acoustic transducers for loan to Navy and other U.S. government activities, commercial activities, and universities.

USRD ACOUSTIC PRESSURE TANK

Provides calibration, test and evaluation measurements over a full range of ocean temperatures and at hydrostatic pressures up to 2700 psi

NAVSEA
NEWPORT
Undersea Warfare Center Division